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ACCUTECH PNEUMATIC FRACTURING EXTRACTION AND HOT GAS INJECTION, PHASE I

Applications Analysis Report

RISK REDUCTION ENGINEERING LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
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Notice

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Foreword

The Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments. The Program is a joint effort between EPA's Office of Research and Development and Office of Solid Waste and Emergency Response. The purpose of the program is to assist the development of hazardous waste treatment technologies necessary to implement new cleanup standards with greater reliance on permanent remedies. This is accomplished through technology demonstrations designed to provide engineering and cost data on selected innovative technologies.

This project consists of a demonstration of the removal of chlorinated volatile organics from vadose zones of low permeability using the Accutech Remedial Systems' Pneumatic Fracturing **Extraction**(SM) process. The project also evaluated the effects, in terms of heat transfer and VOC mass removal, of hot gas injection into the formation. The study was carried out at an industrial park in Somerville, New Jersey where removal of VOC contamination is necessary to comply with New Jersey's Environmental Cleanup Responsibility Act (ECRA).

The goals of the study, summarized in this Applications Analysis Report and described in more detail in the companion Technology Evaluation Report, were to evaluate the pneumatic fracturing and vapor extraction process in terms of VOC mass removal rate and economics and to assess, qualitatively, the effects of hot gas injection. The study also considered the potential applicability of the process to other wastes and/or Superfund and hazardous waste sites.

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E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

Abstract

This document summarizes and analyzes the results of a 4-wk evaluation of the Accutech Remedial Systems, Inc. (ARS) Pneumatic Fracturing **Extraction(SM) (PFE)(SM)** process for increasing the removal of volatile organic contaminants from the vadose zone, particularly where the ground formation is relatively impermeable to air flow. Based on the Superfund Innovative Technology Evaluation (SITE) Program demonstration at an industrial park in Somerville, New Jersey and data from other Accutech investigations, conclusions are presented concerning the technological effectiveness and the economics of the process, and its potential utility for other sites.

During the SITE demonstration, operations were carefully monitored to establish a database against which the vendor's claims for the technology could be evaluated reliably. These claims were that PFE would increase extracted air flow rates from the formation by at least 100% and the mass removal rate for the key contaminant, trichloroethene (TCE), by at least 50%. In addition, although no claim was made, evaluation of hot gas injection was also an objective.

It was found that Pneumatic Fracturing Extraction (PFE) does increase extracted air flow rates by considerably more than 100% and TCE removal rate by much more than the claimed 50% at this site. Specifically, based on comparison of 4-hr test results before and after fracturing, air flow rates were increased >600%, and TCE mass removal rates increased 675%. The increase in TCE mass removal rate appears to be due primarily to the increased air flow since TCE concentrations in the extracted air remained in the 50 to 60 ppmv range. In addition, the extracted air contained significantly higher concentrations of other VOCs after fracturing. The radius of influence for vapor extraction also was greatly enlarged by fracturing. Average extracted air flow rates from peripheral monitoring wells increased by approximately 700% to 1,000% in wells 10 ft away, and 200% to 900% in wells 20 ft away.

With surrounding wells open as passive air inlets, the extracted air flow rate increase after fracturing was even higher, **~19,500%,** and the TCE removal rate increased **~2,300%.**

These results suggest that PFE can make low-permeable formations, such as the bedrock at this site, suitable for vapor extraction. Fewer extraction wells would be required, or remediation could be completed more quickly with PFE, thereby reducing remediation cost.

With PFE, the cost for full-scale remediation of the site was estimated at $307/kg ($140/lb) of TCE removed based on the SITE demonstration experience and information provided by the developer. Major cost factors were labor (29%), capital equipment (22%), VOC emission control (19%), site preparation (1 1%), and residuals management (10%). The nature of the formation, the nature and concentration of the contaminants, and other factors, including site preparations, need for post-treatment, etc., may affect total cost and operating efficiency. The cost estimate should be used with caution.

Based on the results of two experiments, the effects of hot gas injection remain unclear. In one test (90-hr), temperatures in surrounding monitoring wells increased, but TCE mass removal decreased when compared with a pretest without hot gas injection. In a second test (24-hr), TCE mass removal rates increased, primarily due to increased air flow rates, but temperatures did not increase.

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Abbreviations and Symbols

acfm	actual cubic feet per minute
bls	below land surface
BOD	biochemical oxygen demand (mg oxygen/liter)
BTEX	benzene, toluene, ethyl benzene, and xylenes
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
cfm	cubic feet per minute
COD	chemical oxygen demand (mg oxygen/liter)
ECRA	Environmental Cleanup Responsibility Act
GC/MS	gas chromatograph/mass spectrometer
gpm	gallons per minute
HSWA	Hazardous and Solid Waste Amendments to RCRA - 1984
kwh	kilowatt-hour
Mgd	million gallons per day
mg/L	milligrams per liter
NJDEPE	New Jersey Dept. of Environmental Protection and Energy
NAPL	Non-aqueous phase liquid
NPL	National Priorities List
NPDES	National Pollutant Discharge Elimination System
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Administration or Act
OSWER	Office of Solid Waste and Emergency Response
PEL	Permissible Exposure Limit
POTW	publicly owned treatment works
ppb	parts per billion
ppm	parts per million
ppmv	parts per million by volume
psi	pounds per square inch pressure
psia	pounds per square inch pressure, absolute
psig	pounds per square inch, gauge pressure
QA/QC	quality assurance/quality control
RCRA	Resource Conservation and Recovery Act of 1976
RREL	Risk Reduction Engineering Laboratory
SAIC	Science Applications International Corporation
SARA	Superfund Amendments and Reauthorization Act of 1986
scfh	standard cubic feet per hour
scfm	standard cubic feet per minute
SITE	Superfund Innovative Technology Evaluation
TCE	trichloroethene or trichloroethylene
TSDF	treatment, storage, and disposal facility
VOC	volatile organic carbon (mg/liter)

Conversion Factors

	English (US)	x	*Factor*	=	*Metric*
Area:	1 ft^2	x	*9.29 x* 10^{-2}	=	m^2
	1 in=	x	*6.45*	=	cm^2
Flow Rate:	1 cfm	x	*2.83 x* 10^{-2}	=	m^3/min
	1 gal/min	x	6.31 x 10^{-5}	=	m^3/s
	1 gal/min	x	6.31 x 10^{-2}	=	L/s
	1 Mgal/d	x	43.81	=	L/s
	1 Mgal/d	x	3.78 x 10^{3}	=	m^3/d
	1 Mgal/d	x	4.38 x 10^{-2}	=	m^3/s
Length:	1 ft	x	0.30	=	m
	1 in	x	2.54	=	cm
	1 yd	x	0.91	=	m
Mass:	1 lb	x	4.54 x 10^{2}	=	g
	1 lb	x	0.454	=	kg
Volume:	1 ft^3	x	28.32	=	L
	1 ft^3	x	2.832 x 10^{-2}	=	m^3
	1 gal	x	3.785	=	L
	1 gal	x	3.785 x 10^{-3}	=	m^3
Pressure:	1 psia	x	51.71	=	cm Hg

ft = foot, ft^2 = square foot, ft^3 = cubic foot
in = inch, in^2 = square inch
lb = pound
gal = gallon
gal/min (or gpm) = gallons per minute
m = meter, m^2 = square meter, m^3 = cubic meter
cm = centimeter, cm^2 = square centimeter
L = liter
g=gram
kg = kilogram
cfm = cubic feet per minute
L/s = liters/sec
m^3/d = cubic meters per day

Acknowledgements

This project was directed and coordinated by Mr. Uwe Frank, EPA SITE Technical Project Manager in the Risk Reduction Engineering Laboratory - Cincinnati, Ohio.

This report was prepared for EPA's Superfund Innovative Technology Evaluation (SITE) Program under the leadership of Herbert S. Skovronek of Science Applications International Corporation for the U.S. Environmental Protection Agency under Contract No. 68-CO-0048. Major contributors to the program were Susan Christians, Paul Feinberg, Omer Kitaplioglu, and Rita Schmon-Stasik.

The cooperation and participation of John J. Liskowitz of Accutech Remedial Systems, Inc., Professor John Schuring the Hazardous Substance Management Research Center at the New Jersey Institute of Technology throughout the course of the project and in review of this report are gratefully acknowledged. Special thanks are offered to the staff of McLaren/Hart Environmental Engineers, Inc.

Pat LaFonara and Carolyn Esposito of USEPA's Risk Reduction Engineering Laboratory provided invaluable reviews of the draft reports.

Section 1
Executive Summary

Introduction

Accutech Remedial Systems, Inc.'s Pneumatic Fracturing **Extraction**(SM) **(PFE)**(SM) process has been evaluated as a means of remediating a trichloroethene-contaminated vadose zone over a contaminated groundwater zone at an industrial park in central New Jersey. Cleanup of the site is required under New Jersey's Environmental Cleanup Responsibility Act (ECRA) before new construction may be started. Operational and cost data collected in this investigation serve as a basis for an evaluation of the utility of this technology for remediation of this and other VOC-contaminated sites across the nation. Supporting data from other studies of the process at other sites are discussed in Appendix D.

Conclusions

Based on the results of the SITE demonstration project in Somerville, NJ and other information provided by the developers, Accutech Remedial Systems, Inc. (ARS) and the Hazardous Substance Management Research Center (HSMRC) at the New Jersey Institute of Technology (NJIT), several conclusions were reached.

- Pneumatic fracturing does introduce additional fractures into this shale formation and/or enlarges and extends existing fractures, thereby extending the vacuum radius of influence significantly. Extracted air flow through the formation is increased considerably more than the 100% claimed by the developer.

- Largely as a result of the increased extracted air flow rate, and perhaps due to accessibility of new pockets of VOCs, the mass removal rate for trichloroethene also is increased far in excess of the 50% claimed by the developer.

- Specifically, based on 4-hr extraction tests, prefracture air flows of ~0.017 m^3/min (<0.6 scfm increased to 0.112 to 0.168 m^3/min (4.0 to 6.0 scfm or an average increase of >600%. Trichloroethene (TCE) mass removal rates increased from <4.9 mg/min (<1 1 x 10" lb/min) to 38 mg/min (84 x 10^{-6} lb/min), an average increase of over 675%.

- Access to and removal of other VOCs also appears to be improved, since elevated concentrations (and masses) not found in the prefracture extraction test were found in the extracted air after fracturing.

- Based on extraction tests from the peripheral monitoring wells, average air flow rates were increased from 700% to 1,000% in wells at a 10 ft distance, and even 200% to 900% in wells 20 ft from the fracture well.

- The spatial uniformity of fracturing may be affected by geological and man-made heterogeneities in the formation. Fracturing effects may be unpredictable in a heterogeneous formation; man-made structures, e.g., building foundations, sewer and utility lines, etc., may affect the extent, direction, or effectiveness of fracturing.

- Water in the formation may have removed additional TCE (and other volatiles), but may also have adversely affected the air flow and, in the hot gas injection experiments, heat transfer.

- With radially placed wells open as passive air inlets, significantly higher extracted air flow rates (19,500% increase) were obtained after fracturing and the TCE mass removal rates also were increased (2,300%).

- The total cost for Pneumatic Fracturing Extraction is estimated at \$307/kg or \$140/lb of TCE removed based on the demonstration. Major cost factors were: labor (29%), capital equipment (22%), VOC emission control (19%), site preparation (11%), and residues management (10%). Several assumptions were made in developing this cost estimate.

- The major advantages of Pneumatic Fracturing Extraction are (a) the increase in air flow and VOC removal achievable in "tight" rock formations; (b) the reduction in the number of wells that should be needed to remediate a specific site, i.e., greatly extended radius of influence for a given number of wells; (c) decreased time required to remediate a given area to a certain level; and (d) elimination of the need to excavate and treat large volumes of soil.

- The equipment needed to support this process is considerably less than that which would be needed for aboveground treatment systems such as incineration or soil washing. Compared to conventional soil vapor extraction, if that can be used cost-effectively, the only additional equipment needed is a packer system and a source of compressed gas for fracturing. Aboveground treatment of the VOC vapors would require similar equipment, such as carbon adsorption, incineration, or catalytic destruction for either extraction process.

- With proper selection and characterization of a site, Pneumatic Fracturing Extraction should be well suited to the treatment of vadose zones of low permeability containing a wide range of VOC pollutants.

- The measurable effects of hot gas injection remain unclear. In one experiment of 90-hr duration, extraction and monitoring well temperatures did increase, but TCE mass removal rates decreased. In a second experiment (24-hr), increased air flow rates resulted in increased TCE mass removal rates, but no temperature increase was observed.

Discussion of Conclusions

A mobile PFE system consisting of a source of compressed air, a means of injecting the pressurized air into the ground, and a conventional vapor extraction system was evaluated under the Superfund Innovative Technology Evaluation (SITE) program. Extensive data were collected over about a 4-wk period (a) to compare the ability of the extraction system to remove TCE and other VOCs from the vadose zone before and after pneumatic fracturing; (b) to identify the operational requirements of the system; and (c) to establish bases for estimating the cost of operation. In addition, two experiments, one of 90-hr duration and one of 24-hr duration, were carried out to evaluate hot gas injection. The data from these tests serve as the primary basis for the foregoing conclusions. Additional information from other field studies was provided by Accutech and HSMRC.

An extensive Quality Assurance (QA) program was conducted by SAIC in conjunction with EPA's QA program, including audits and data review along with corrective action procedures to correct specific problems. This program assured the quality of the data derived from the SITE project. Discussion of the QA program and the results of audits, data reviews, corrective actions, etc. can be found in the Technology Evaluation Report.

Well placement was designed so that the extracted air flow rates in all directions and TCE concentrations could be assessed before and after fracturing. The primary evaluation consisted of 4-hr tests before and after fracturing. Shorter tests and visual examination by borehole camera were used to measure the effectiveness of fracturing and to provide evidence of connections due to fractures. Extensive data were collected on air flow rates, pressures, and TCE concentrations. All results are corrected to standard conditions (1 atm, 60°F).

The results of the SITE project demonstrated that PFE created and/or enlarged fractures in the formation, increased connections between wells, and made increased removal of TCE possible (Table 1). Unexpected perched water in the vadose zone appeared to interfere with air movement between wells, but VOC-laden air still could be extracted after fracturing at rates far above that claimed by the developer.

Table 1. Effects of Fracturing, 4-hr Tests

Parameter	Prefracture	Prefracture Restart	Postfracture
Pressure, psia	11.1	11.1	11.4
Air flow, scfm	<0.6*	<0.6*	4.2±0.6
TCE mass removal, 10^{-6}lb/min	<10.9	<11.0	83.9±31

* HSMRC data indicate air flow <0.6 scfm.

Based on the demonstration, there are several factors that could be critical to cost-effective PFE operation at other sites. First among these is the geological character of the vadose zone formation, particularly its permeability, i.e., how easily and effectively conventional soil vapor extraction could be applied. Second is the spatial uniformity of the formation. Natural fractures or ease of fracturing may affect the extent and direction of fracturing and, consequently, the number and placement of wells needed for remediation. The presence of water in the vadose zone and the solubility of contaminants in the water will also be factors. Finally, any preferential pathways such as buried sewers, pipelines, building foundations, etc. may influence the direction, extent, and possibly the safety of pneumatic fracturing. Another factor to consider when comparing remediation options would be the concentration of key pollutants that would reach the aboveground air treatment system. Low concentrations may be more appropriately adsorbed on carbon while higher concentrations (e.g., >50 ppm) may be more economically incinerated or destroyed by catalytic systems.

Hot Gas Injection (HGI) experiments were carried out to provide data on the transfer of heat to the formation and TCE removal rate. In the first (90-hr) experiment, increases in extraction and thermal monitoring well temperatures were observed, but accompanied by a decrease in TCE mass removal rate when compared with a baseline experiment without hot gas injection. A second experiment (24-hr) was conducted using new wells in an area where successful horizontal fracturing had occurred and where higher TCE concentrations were anticipated. In this case, increased TCE mass removal rates, corresponding to increased air flow rates, were observed, but with no temperature increases.

Several factors may contribute to the anomalous results in these HGI experiments, including the nature of the baseline experiments used for comparison and the variable presence of water in the zone. It remains unclear from the experimental results whether injection of hot air can increase VOC mass removal rate. Permeability of the formation, water content, heat capacity of the formation, etc. all may affect heat transfer. Even where good connection exists between injection and extraction wells, removal of VOC contaminants may be limited by diffusion or desorption rate rather than dependent on the increased volatilization induced by any heat transferred to the formation.

Section 2
Introduction

The SITE Program

The EPA's Office of Solid Waste and Emergency Response (OSWER) and the Office of Research and Development (ORD) established the Superfund Innovative Technology Evaluation (SITE) Program in 1986 to promote the development and use of innovative technologies to clean up Superfund sites across the country. Now in its eighth year, the SITE Program is helping to provide the treatment technologies necessary to implement new federal and state cleanup standards aimed at permanent remedies, rather than quick fixes. The SITE Program is composed of four elements: the Demonstration Program, the Emerging Technologies Program, the Monitoring and Measurement Technologies Program, and the Technology Transfer Program.

The major focus has been on the Demonstration Program, which is designed to provide engineering and cost data on selected innovative technologies that are in an advanced stage of development. To date, the demonstration projects have not involved funding to technology developers. EPA and the developers participating in the program share the cost of the demonstration. Developers are responsible for demonstrating their innovative systems at chosen sites, usually Superfimd sites, although in this case a NJ ECRA site was selected. EPA is responsible for developing a mutually acceptable evaluation protocol, sampling and analyzing specified streams, and evaluating all test results. The result is an independent assessment of the technology's performance, reliability, and cost. This information will be used in conjunction with other data to select the most appropriate technologies for the cleanup of Superfund sites and other sites contaminated with hazardous wastes.

Developers of innovative technologies apply to the Demonstration Program by responding to EPA's annual solicitation. To qualify for the program, a new technology must have a pilot- or full-scale unit and must offer some expected advantage over existing technologies. Mobile and in situ technologies are of particular interest to EPA.

Once EPA has accepted a proposal, the Agency and the developer work with the EPA Regional offices and state agencies to identify a site containing wastes suitable for testing the capabilities of the technology. EPA designs a detailed sampling and analysis plan to evaluate the technology thoroughly and to ensure that the resulting data are reliable. The duration of a demonstration varies from a few days to several months, depending on the type of process and the quantity of waste needed to assess the technology. Although it may be possible to obtain meaningful results in a demonstration lasting one week for an incineration process where contaminants are destroyed in a matter of seconds, other technologies where contaminant variability, system acclimation, and system stability must be examined may require an extended period of time. For Pneumatic Fracturing Extraction, it was determined that approximately two weeks of operation, with key tests lasting several hours before and after fracturing, would be indicative of the effectiveness and utility of the process. To evaluate the effects of Hot Gas Injection, a test lasting several days was desirable.

After completing the demonstration, EPA prepares two reports which are explained in more detail below. Ultimately, the Demonstration Program leads to an analysis of the technology's overall applicability to Superfund problems.

The second principal element of the SITE Program is the Emerging Technologies Program, which fosters the investigation and development of treatment technologies that are still at the laboratory scale. Successful validation of these technologies can lead to the development of systems to a stage ready for field demonstration. The third component of the SITE Program, the Measurement and Monitoring Technologies Program, provides assistance in the development and demonstration of innovative technologies to more efficiently characterize Superfund sites. As part of the Technology Transfer Program, a Technology Evaluation Report and an Applications Analysis Report are published at the conclusion of each demonstration. Research reports on emerging technology projects are also produced. Results and status updates are distributed to the user community, including EPA Regions, state agencies, remediation contractors, and responsible parties, through many media and activities.

SITE Program Reports

The results of the SITE Demonstration Program are incorporated in two basic documents, the Technology Evaluation Report and the Applications Analysis Report. The former provides a comprehensive description of the demonstration and its results. The anticipated audience will be industrial and governmental engineers responsible for detailed evaluation of technologies for other sites and contaminant situations. These technical evaluators will want to understand thoroughly the performance of the technology during the demonstration and the advantages, risks, and costs of the technology for the given application.

The Applications Analysis Report is directed to decision-makers responsible for selecting and implementing specific remedial actions. This report provides sufficient information to determine if the technology merits further consideration as an option in cleaning up specific sites. If the candidate technology described in the Applications Analysis Report appears to meet the needs of a site, a more thorough analysis of the technology will be made based on the Technology Evaluation Report and other information such as previous remedial investigations for the specific site. In summary, the Applications Analysis Report will assist in determining whether the specific technology should be considered further as an option for a particular cleanup situation.

Purpose of the Applications Analysis Report

Each SITE demonstration will evaluate the performance of a technology while treating the particular waste found at the demonstration site. Additional data from other projects also will be presented where available to assist in evaluation of the applicability.

Usually the waste at other sites being considered for remediation will differ in some way from the waste tested. Waste and site characteristics could affect treatability, cost, and the advisability of using the demonstrated technology at other sites. Thus, successful demonstration of a technology at one site does not assure that a technology will work equally well at other sites. The operating range over which the technology performs satisfactorily can only be determined by examining a broad range of wastes and sites. The Applications Analysis Report provides an indication of the applicability of the demonstrated technology, Pneumatic Fracturing Extraction in this case, by examining not only the demonstration test data, but also data available from other field applications of the technology.

To encourage the general use of demonstrated innovative technologies, EPA evaluates the probable applicability of each technology to sites and wastes in addition to those tested, and studies the technology's likely costs in these applications. The results of these analyses are summarized and distributed to potentially interested parties through the Applications Analysis Report.

Key Contacts

For more information on the demonstration of the Accutech Pneumatic Fracturing Extraction and Hot Gas Injection processes for decontamination of low permeability vadose zones, please contact:

1. Vendor concerning the process:

   Harry Moscatello, President
   John J. Liskowitz, Development Engineer
   Accutech Remedial Systems, Inc.
   Cass Road at Route 35
   Keyport, New Jersey 07735
   908-739-6444

   and

   Prof. John Schuring, Ph.D.
   Hazardous Substance Management Research Center
   New Jersey Institute of Technology
   Newark, New Jersey 07102
   201-596-5849

2. EPA Technical Project Manager concerning the SITE Demonstration:

   Mr. Uwe Frank
   U.S. EPA - ORD
   Releases Control Branch (MS- 106)
   2890 Woodbridge Avenue
   Edison, NJ 08837-3679
   908-321-6626

3. Contact concerning the site:

   Mr. James Mack
   McLaren/Hart Environmental Engineers, Inc.
   25 Independence Boulevard
   Warren, New Jersey 07059
   908-647-8111

Section 3
Technology Applications Analysis

Introduction

This section of the report addresses the potential applicability of the Accutech Pneumatic Fracturing Extraction (PFE) process to various other contaminants, formations, and Superfund site situations where volatile organic pollutants are of primary interest. The demonstration provided an extensive database for this process and serves as a foundation for conclusions on the effectiveness and the applicability for cleanup of other sites. Supporting information provided by the developer is also referred to when considering the applicability of the technology to other situations.

The following subsections summarize conclusions and observations drawn from the current study and supporting information. Included are factors such as contaminant types, site characteristics and constraints, applicability and impact of state and federal environmental regulations, unique handling or operating requirements, and personnel requirements. Additional information on the ARS technology, including a process description, vendor claims, a summary of the Demonstration test results, and Case Studies of other investigations is provided in the Appendices.

Conclusions

Based on the results of the demonstration study and other information provided by the developer, the vendor's claims are substantiated.

The Pneumatic Fracturing Extraction process can increase air flow through relatively non-permeable vadose zone formations by 400 to 700%, averaging 600% at this site. The increase may not be uniform in all directions nor at all depths, depending on the character of the formation and other influences.

With the increase in extracted air flow, the removal of VOCs, in terms of mass of trichloroethene (TCE) removed per unit time, is also increased, approximating 675%, based on the comparison of results of 4-hr tests before and after fracturing. Fracturing of the vadose zone also appears to have increased the accessibility and removal of other chlorinated hydrocarbons and benzene which had not been detected during vapor extraction before fracturing.

Based on short duration (10-min) extraction tests at the monitoring wells, PFE increased the permeability of the formation, in terms of average extracted air flow rate, between 700% and l,000% in wells at 10 ft and 200% and 900% in wells 20 ft from the fracture well.

Allowing air to enter at four wells (passive air inlet) while extracting from the fracture well produced even larger increases in air flow and TCE mass removal rates, approximately 19,500% and 2,300%, respectively. When compared to the postfracture extraction with wells capped, TCE mass removal rate was increased 38%.

The costs for the PFE process are estimated on the basis of the pilot plant and other data provided by Accutech and HSMRC. For a surface area of 15,000 ft^2 and a vadose zone depth of 20 ft, a predicted fracturing radius of 25 ft with 15% to 20% overlap, 15 fracture/extraction wells would have to be installed to cover the area. On this basis, the estimated cost for a I-yr cleanup effort is $307/kg or $140/lb of TCE removed. Labor is the major cost factor, accounting for 29%; capital equipment accounts for 22%; and collection and disposal of VOC emissions accounts for another 19% of the costs. Site preparation and residuals disposal account for 11% and 10%, respectively.

The PFE process provides a means of carrying out vapor extraction of volatile contaminants from low permeability formations such as bedrock, where poor permeability and poor connection between extraction well and a source of air would normally preclude such a process. This may provide an attractive ‘alternative to costly excavation and ex-situ treatment.

The system is simple to operate and requires a minimum of operator attention or maintenance once fracturing has been accomplished. The pneumatic fracturing is a rapid operation that can be applied over an extended area at relatively low cost. Vapor extraction also is a relatively low cost operation, although treatment of the extracted vapors can affect economics.

The impacts of hot gas injection into the fractured formation, in terms of heat transfer, air flow, and TCE mass removal, were unclear and remain open to interpretation. In one experiment, increases were observed in well temperature (to 45°F to **85°F),** but TCE mass removal decreased. A second, shorter experiment provided contradictory results: increased TCE mass removal rates at increased injected (and extracted) air flow rates, but no elevated temperatures in the extraction wells.

Discussion of Conclusions

The developer originally had proposed an extensive program integrating PFE with catalytic oxidation of extracted chlorinated volatile organics and injection of the exhaust gas from the catalytic oxidation unit. Sufficient information was not available for this site at the outset of this demonstration to justify such an expenditure of time and resources by all parties. Consequently, a Phase I study consisting of short term tests was considered a practical and cost-effective means of obtaining a reliable evaluation of the primary technology, PFE. EPA would then be able to make an informed decision concerning a more extensive Phase II study of the PFE technology, catalytic oxidation (Catox), and Hot Gas Injection (HGI).

The SITE Program demonstration in Somerville, New Jersey clearly indicated that fracturing was an attractive means of increasing the removal of volatiles from a low-permeable vadose zone with minimum disturbance of the formation or the surface. Figure 1 conceptually describes a bedrock formation before and after fracturing. Figure 2 indicates the location of the wells used in this investigation of Pneumatic Fracturing Extraction, including monitoring wells that could be used as injection or extraction wells in a more extensive test or remediation (see next pages).

Air Flow Increase with Fracturing

Based on pressure and air flow measurements at the fracture well and at monitoring wells before and after fracturing, it is concluded that the connectivity between wells can be considerably increased by fracturing but may vary with direction, distance, and the nature of the formation between two wells. Surprisingly, the existing strike and dip direction did not have an impact on the fracturing pattern and preferential air flow was not observed. The results in Table 2 were obtained during 10-min extraction tests at each monitoring well before and after fracturing.

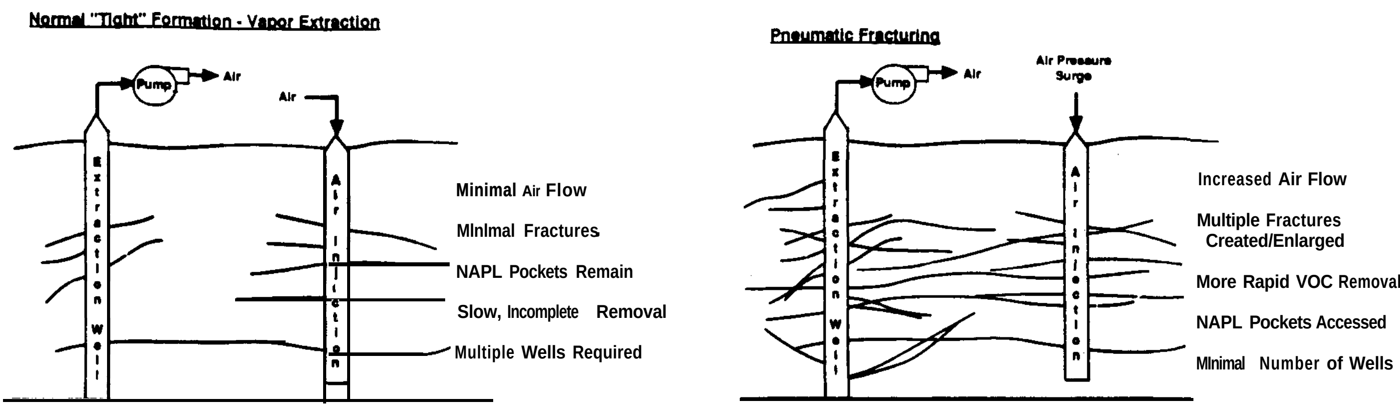


Figure 1. Conceptual Schematic of Pneumatic Fracturing.

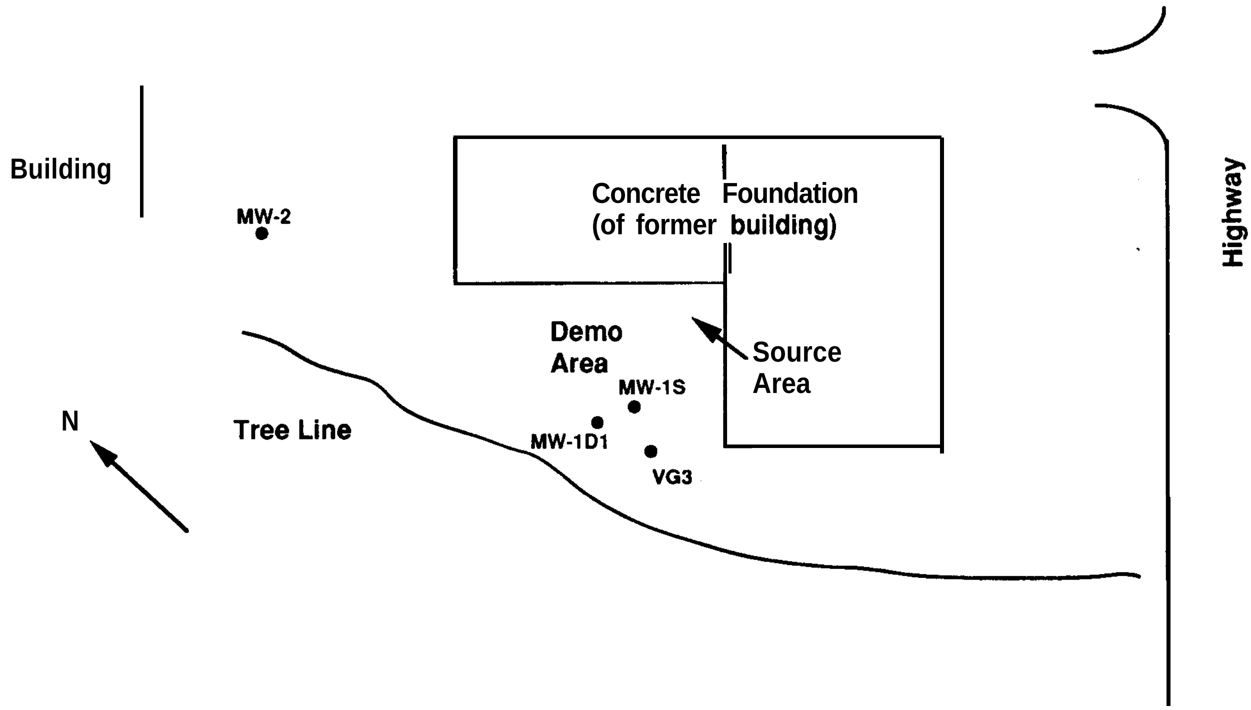


Figure 2. Site plan with pre-existing wells,

Table 2. Monitoring Well Extraction Tests

Distance from FW, ft	Well No.	Air flow rate, scfm avg pre-fracture	Air flow rate, scfm avg post-fracture	Increase, % avg
7.5d*	FMW 6	<.89^	6.1	>580
10 s	FMW 1	<.63	5.6	>790
10 o/s	FMW 2	<.74	6.1	>720
10 d	FMW 3	<.63	7.2	>1040
10 s	FMW 4	<.63	6.9	>990
20 s	FMW 5	<.63	6.5	>930
20 d	FMW 7	<.63	2.0	>220

^ prefracture air flows based on HSMRC data.
* s = strike; d = dip; o/s = off strike and dip

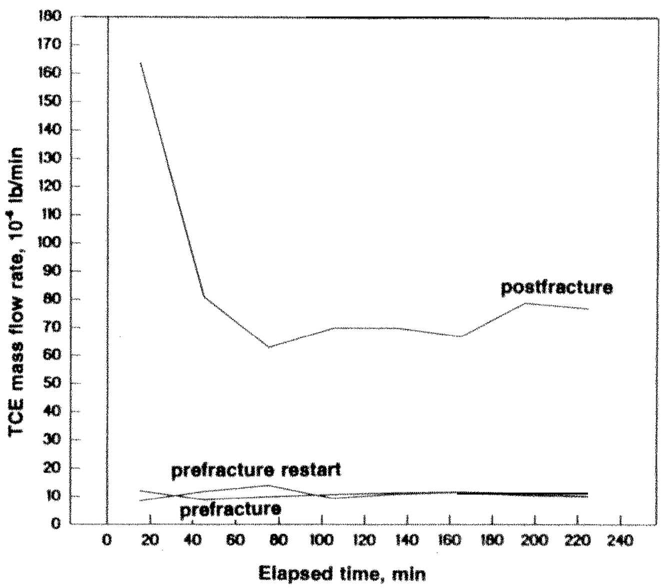


Figure 3. Comparison of 4-hr TCE mass removal rates.

Increase in Trichloroethene Removal with Fracturing

Field analyses before and after fracturing indicated that the mass of TCE removed over the course of the 4-hr test period paralleled the increase in air flow. On the basis of these results (Table 1, earlier), the developer's claim that the mass removal rate for TCE from the formation could be increased by 50% or more was clearly validated and considerably exceeded. Figure 3 graphically presents the increase in TCE mass removal achieved by fracturing in the 4-hr tests.

The experiments examined the relatively short term (4-hr) benefits of fracturing; extrapolation to long term benefits, e.g., total VOC removed or the final concentrations in the formation, should be done with extreme caution. For example, the data clearly show larger TCE mass removal rates during the first 30 min of testing, particularly during the postfracture test.

Analysis of samples by gas chromatography/mass spectrometry (GC/MS) confirmed TCE as a major contaminant before fracturing and confirmed the field GC indications of significantly higher concentrations for several other contaminants after fracturing, including other chlorinated hydrocarbons and benzene (Table 3). Fracturing may have provided access to pockets of these NAPLs (non-aqueous phase liquids). Considering the very large increases in air flow after fracturing, removal of such other contaminants becomes very significant.

Table 3. VOCs in Extracted Air, Before and After Fracturing

Contaminant	Concentration, ppmv Prefracture	Postfracture
Methylene chloride	1.4	26.0
Chloroform	3.5	108.5
c-1,2-dichloroethene	U (<3)	U (<12.5)
Trichloroethene	59.4	113.4
Benzene	5.4	412.7
Tetrachloroethene	3.3	220.4
Toluene	U (<3.3)	5.2J
Xylene, m/p-	U (<2.8)	U (<11.4)
Xylene, o-	U (<2.8)	U (<11.4)

U = below detection limit
J = estimated, below quantitation limit

Additional tests were carried out by extracting from the fracture well while up to 4 of the monitoring wells were left uncapped to allow for passive air inlet. Under these conditions, the extracted air flow and TCE mass removal rates after fracturing increased even more dramatically when compared with the prefracture results (Table 4), although air flow rate increased more than TCE mass removal rate.

Table 4. Passive Air Inlet Tests

Parameter	Prefracture	Postfracture	Increase, %
Pressure, psia	10.8	14.6	---
Air flow, scfm	0.39±.04	76.4±4.8	19,500
TCE mass removal, 10^{-6}lb/min	4.79±1.4	116.0±91	2,270

Operational Reliability/Stability

The extraction system proved to be quite stable and required a minimum of attention over the course of the 4-wk study. Unexpected water in the vadose zone did present a problem, and it was found necessary to pump the wells daily, prior to each day's tests, to assure that the needed open zone (from the 8 ft deep casing to the -20 ft well bottom) was available for testing. Obviously, some TCE was removed in this water as well, but, because of the nature of the test program, this removal route was considered outside the scope of the study. Although this contribution to TCE mass removal was not routinely measured, analyses for disposal indicated TCE concentration to be -100 ppb. Other than this pumping, which might or might not be needed at other sites, little attention to the system was necessary once the fracturing was completed and the extraction system had been stabilized. The exhaust vapors were passed through a granular activated carbon adsorption train to remove the VOCs and the exhaust was checked daily by OVA for total VOCs to assure that contaminant breakthrough into the atmosphere was not occurring.

Similarly, during Hot Gas Injection a minimum of attention was required once compressor pressure and air flow had been adjusted to maintain a constant injection temperature (-200°F to 250°F). In a fully integrated system, where hot gas (-1000°F) would be generated as a by-product of catalytic oxidation of VOCs, some additional attention may be needed to maintain temperature balance as the concentration of VOCs in the extracted gas and the amount of heat resulting from VOC decomposition decreases.

Costs

Cost data were developed for a hypothetical 40 hp (500 cfm) extraction unit on the basis of experience during the SITE demonstration, assuming that wells would be spaced in accordance with the fracture/extraction radius observed in the demonstration. The major cost factors for PFE were found to be the labor required during fracturing and to oversee the ongoing vapor extraction (29%); the amortized cost of capital equipment (22%); collection of VOCs on activated carbon (19%); site preparation (11%); and management of residuals (10%). In the absence of a catalytic oxidizer for the TCE (and other volatiles) in the extracted gas, use of carbon adsorption for emission control would be continued and, as noted, contributed significantly to overall cost.

For this cost estimate, it was assumed that water would be present in the vadose zone, as at the demonstration site. In the demonstration, this water was accumulated in a tanker truck and disposed of off-site at a cost of about $l/gallon as hazardous waste. A more realistic alternative for a larger scale remediation would be to air strip this perched water on-site together with the groundwater and adsorb the volatiles on carbon until a catalytic oxidation unit is available. The cost for the carbon canisters used for emission control in the demonstration, including carbon disposal and replacement, was $1120/drum, or about $4/lb of carbon. Combining the water streams, air stripping, and carbon adsorption was selected as the most realistic option for the hypothetical cost model; no incremental cost for stripping or the carbon used for the VOCs from the perched water was included.

It would not be meaningful to estimate the cost parameters for Hot Gas Injection on the basis of this demonstration. Production of hot air, as done in the demonstration by compression of air, is not the intended approach in a remediation; hot gas production cost would be a derivative of the catalytic destruction cost and was not considered in this analysis.

Applicable Wastes

Although this study of the Accutech Pneumatic Fracturing Extraction system was directed to trichloroethene, which was expected to be the predominant contaminant in the vadose zone at the site, the technology should be equally well suited to other volatiles, both chlorinated and non-chlorinated, as suggested by the removal of other volatiles (BTX) during the postfracture segment of this demonstration and in results provided by the vendor for other sites. These may be present as adsorbed material, dissolved in water, or as pockets of "NAPLs", non-aqueous phase liquids. Such NAPLs can be lighter than or heavier than water. The design of the system is such that even elevated concentrations of contaminants in the vadose zone should not affect operation, except in determining the length of time the system may be needed at a particular site to achieve a specified removal or final concentration. In addition, the choice of final treatment for the extracted volatiles (e.g., stripping, incineration, or carbon) and the scaling of that treatment system would also be dependent on the nature of the VOCs and their concentrations, as in any vapor extraction.

Ground temperatures, water in the vadose zone, solubility of the VOCs in water, volatilization rates, and the vapor pressure of the VOCs also could affect the operation and cost of the PFE process, but were not studied in the demonstration.

Other pollutants in the vadose zone should not adversely affect the operation of the system except that, if extracted into the air stream, their removal would have to be addressed. And, if Hot Gas Injection were used to accelerate VOC removal from a site, transfer of semivolatiles into the gas stream may increase simultaneously. As noted, however, the demonstration results did not consistently indicate increased TCE removal rates from the injection of hot air (200°F to 250°F).

Site Characteristics

Vapor extraction is an appropriate innovative removal approach for VOCs from unsaturated ground formations where sufficient air flow for extraction can be achieved. PFE would offer an attractive alternative for formations which have insufficient air permeability for conventional vapor extraction. This could include shales such as the Brunswick formation, found widely across the northern part of New Jersey, as well as silts and clays of low permeability. Such geological characteristics may be found elsewhere in Superfund and RCRA sites. Other studies by HSMRC have shown that the benefits of fracturing, in terms of increased permeability, are inversely related to soil particle size, and that the technique can improve vapor extraction effectiveness, even in more permeable soils, although not to as great an extent. Appendix D presents summaries of such evaluations.

Since the fracturing wells are best left uncased to allow fracturing in several narrow intervals, the formation must have enough integral strength not to collapse or recompress during well drilling, fracturing, or vapor extraction. Although some settling of fractures with time may be tolerable, ideally the voids created or enlarged during fracturing must remain open for air flow or re-fracturing may be required. Finally, the nature of the formation must be such that preferential horizontal fracturing occurs, rather than vertical fracturing, particularly where the water table is close to the zone being fractured and, could be contaminated further by vertical movement of contaminants.

Extensive three-dimensional characterization of the formation (including water levels, natural fractures, strike and dip orientation, etc.) would be helpful in planning the well field and anticipating the radius of influence of each fracturing effort at a particular site. Obstacles such as building foundations, underground utilities, and sources of "short circuiting" such as pipelines, permeable soil lenses, etc., need to be identified and, if possible, avoided or at least factored into the cleanup plan. For example, during fracturing at the demonstration site, an unexpected escape of air and vapors occurred at an abandoned and unmarked borehole about 30 ft from the fracture well.

To date, PFE has been applied to the decontamination of the unsaturated zone. However, in some situations it may also be used cost-effectively to treat NAPLs in saturated zones, where the water table can be lowered by pumping or natural drying (e.g., seasonal), leaving the NAPLs absorbed in the dewatered formation. Presumably, any water pumped from such a site would require some treatment to remove and treat the dissolved or dispersed organics in the water. Research at HSMRC has also developed evidence that fracturing can be carried out in a saturated zone without dewatering and subsequent VOC removal by a combination of stripping and vapor extraction is enhanced.

The mobile extraction system and the staging area for the compressed air source used in the demonstration program required only a level work area of approximately 50 ft by 50 ft. Electrical power for the extraction unit and for pumping of well water was provided by temporary service to the site, but a diesel generator could be used just as effectively. Obviously, the site must be sufficiently accessible to allow a drill rig to be positioned for the installation of the necessary wells.

Depending on local, state, and federal requirements, extracted VOCs may be emitted into the atmosphere (unlikely), adsorbed from the extracted air on carbon as was done during the demonstration, or destroyed by incineration or the proposed catalytic oxidation. Water pumped from the formation would presumably contain the contaminants (both volatiles and others) present in the zone and could require treatment to meet discharge or reinjection requirements. Since vapor concentrations suitable for PFE are equivalent to significantly lower concentrations in the water phase, any wastewater may be acceptable for discharge to surface water or to a POTW without pretreatment.

Environmental Regulation Requirements

A first concern would be state or local well-drilling requirements, including permits and management of well cuttings. In some cases, as at the demonstration site, there may be concern about penetration of the wells into the underlying groundwater. This was originally expressed in DEPE's review comments concerning the ECRA Cleanup Plan, where well depth was limited to 25 ft.

Water removed during well drilling or subsequently must be disposed in accordance with federal and/or state regulations, as a hazardous waste if it contains sufficiently high concentrations of VOCs or other contaminants (organic and inorganic). Treatment (e.g., air stripping) may be required before the water can be discharged to surface water or introduced into a POTW as non-hazardous. Such ancillary activities may require a NPDES Permit or a RCRA Part B permit as a TSD facility. And, depending on the volume, rate of production, and characteristics of the water, any tanks used for storage or to provide equalization may themselves need regulatory attention (permits, design, etc.), depending on their size and placement.

The removal, treatment, and disposal of groundwater was not part of this project but is addressed for this site in the ECRA Cleanup Plan. State or federal permitting would be required for treatment and discharge of any such groundwater at other sites, as well.

Under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and the Superfund Amendments and Reauthorization Act of 1986 (SARA), EPA is responsible for determining the methods and criteria for the extent of removal of hazardous contaminants from Superfund sites. The utility and cost effectiveness of the PFE system would, at such sites, be at least partially dependent on the final level deemed appropriate and necessary at a particular site. However, since the use of remedial actions by treatment that "...permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances" is strongly recommended (Section 121 of SARA), the PFE system coupled with appropriate aboveground treatment would appear to be an attractive remedy for a site where the vadose zone is contaminated with hazardous VOCs.

SARA also requires consideration of potential contamination of the ambient air and general criteria requiring remedies that protect human health and the environment. Any vapor extraction process such as PFE would probably require further treatment of emissions, such as catalytic oxidation or carbon adsorption (and disposal of carbon) to assure that hazardous VOCs are not emitted to the ambient air. Depending on the location of a site, this might be addressed as part of an air emissions or a hazardous waste permit. The overall impact of the Clean Air Act of 1990 is not yet clear, but a permit may be required if certain VOCs are present or the quantity of emissions is large.

At the demonstration site, fugitive VOC emissions occurred during the initial stages of Hot Gas Injection. From both a worker safety and an environmental point of view, it would be necessary to assure, to the maximum extent possible, that such "short circuiting" through vertical fractures, sewer lines, etc., did not occur during a site remediation. Although OSHA does not issue permits, it would be an operator's responsibility to monitor and document that emitted concentrations of VOCs were below allowable airborne concentrations. For example, the current Permissible Exposure Limit (PEL) for TCE is 100 ppmv; a new standard, currently in litigation, would reduce this exposure limit to 50 ppmv.

Chlorinated ethenes and ethanes in groundwater occasionally have been found to produce vinyl chloride, probably by anaerobic biodegradation. Although none was found at the New Jersey site, characterization of other sites should probably include measurement for vinyl chloride and dichloroethenes and additional controls if these species are present in significant concentrations. The PEL for vinyl chloride is 1.0 ppmv; it will not change with the new OSHA standards.

The use of Hot Gas Injection could raise several additional regulatory issues. Accutech has proposed that the hot exhaust gases from catalytic oxidation of the VOCs be injected directly. Since these gases may be contaminated, as with HCl from the destruction of halogenated VOCs, direct injection may not be acceptable unless it can be demonstrated that such contaminants do not adversely affect the formation or leach into groundwater at the site. For example, acid gases could solubilize metals in the soil. Such situations could be avoided by scrubbing the gas prior to injection or by using a heat exchanger.

Materials Handling Requirements

The materials handling requirements for the Pneumatic Fracturing Extraction process are quite limited since the process is carried out "in situ", at least relative to excavation. The site must be able to support a well drilling rig capable of drilling through shale or other relatively impermeable formations.

Full-scale remediation of a site using PFE must be designed with appropriate air treatment to remove the extracted VOCs (and semivolatiles) from the air stream before it is exhausted to the environment. Carbon adsorption may be the most appropriate method for low concentrations (and masses) of contaminants, but alternate means, such as the catalytic oxidation proposed for Phase II study by Accutech, may be more cost-effective at higher (>50 ppmv) concentrations. Similarly, any water removed from the formation before, during, or after fracturing or vapor extraction would also require treatment prior to discharge. This can be accomplished by stripping and carbon treatment or, as suggested by Accutech for Phase II study, by stripping and catalytic oxidation of the vapors.

Although the matter was not investigated as part of this Phase I demonstration, it may be necessary to use high temperature grout when installing well casings that will be exposed to extreme heat during Hot Gas Injection from catalytic destruction. Some products exist to meet this need.

Personnel Issues

Well drilling also would be a labor-intensive phase of the Pneumatic Fracturing Extraction process. Although a certain number of wells covering the area being remediated can be installed at the outset, additional wells may be needed as the actual radius of influence resulting from each fracturing well is determined.

Except during the well drilling and the actual fracturing, installation and operation of the PFE system requires little attention. Although a number of personnel were needed during the demonstration to observe and record data at the several wells and other tasks, vapor extraction normally operates unattended once steady state operation is achieved. If the water table must be suppressed or perched water must be pumped out to provide an unsaturated zone for fracturing and extraction, then the labor requirements could increase somewhat. Less labor-intensive operation could be achieved with automatic level-activated pumps.

Treatment of extracted vapors (and pumped water) may also increase manpower requirements slightly but, again, these operations can usually be unattended once a steady state is established.

Testing Issues

Probably the most important testing' for the use of Accutech's Pneumatic Fracturing Extraction process takes place during site characterization and includes profiling the formation and determining the nature and concentrations of contaminants in the strata. This makes it possible to plan the most efficient well field and fracturing protocols for the site with minimal risk of groundwater contamination or short circuiting to the surface. Such a testing program would entail groundwater flow measurements, air permeability tests, geological characterization, contaminant characterization, documentation of all underground utilities, and where possible, soil gas or other vapor phase analysis of VOCs in the vadose zone.

Pressure and air flow measurements can be indicators of extraction efficiency, but pollutant-specific analysis ultimately is necessary. Because of the rapid changes in VOC concentrations expected during the demonstration, on-site monitoring of the extracted air by gas chromatography of Tedlar bag samples was selected as the most cost-effective methodology. It was found that the number of analyses that could be carried out within

Method 18 specified Tedlar bag holding time (2 hr) was limited, particularly when numerous volatile constituents were present in the extracted gas. During remediation of larger sites, this should not be a problem since such an extensive evaluation of the offgases should not be necessary. If variable concentrations or compositions are anticipated, or if significant concentrations of semivolatiles are expected as well, more complete GC/MS analyses may be desirable. In those cases, collection of air samples in Summa canisters or on adsorbents may be necessary to allow for the more time-consuming analyses, using EPA standard methods, unless an on-site GC/MS is available.

Once characterization has been completed, routine semi-quantitative monitoring by instruments such as the OVM may be sufficient. Portable organic vapor analyzers should also be in use at the site to monitor VOC levels during drilling and to detect any unexpected vertical fracturing leading to short-circuiting to the surface, as was encountered during Hot Gas Injection at the demonstration site. This will provide protection for workers and the ambient air. The portable vapor analyzers, coupled with quantitative and pollutant-specific analysis by GC or GC/MS, also may be needed to fulfill air permit requirements.

Section 4
Economic Analysis

Introduction

The primary purpose of this economic analysis is to estimate costs for commercial-scale remediation using the Accutech PFE system based on the experience gained during the demonstration. With realistic costs and a knowledge of the bases for their determination, it should be possible to estimate the economics for operating similar-sized systems as well as larger systems at other sites utilizing various scale-up approaches and cleanup scenarios.

Cost and efficiency for vapor extraction are dependent on the concentration present, the area1 extent of contamination, the distribution of contaminants among different matrices, and soil characteristics, e.g., air permeability, etc. One key factor that may not be accurately predictable without a pilot test is the radius of influence and, consequently, the number of wells needed to remediate a particular site. The cost of conducting such a pilot study is not included here.

Although the cost of remediation is often presented in terms of dollars to achieve a final cleanup level on the site, that approach could not be applied in this situation because no final cleanup criteria for the air or soil had been established. Instead, costs in twelve categories for an assumed 1-yr cleanup time were estimated. As in the SITE demonstration, the primary contaminant of interest was assumed to be trichloroethene (TCE). The sum of these costs was then divided by the total mass of TCE that could be removed in the same 1-yr time period, assuming that the performance of a commercial-scale remediation would be comparable to that demonstrated under the SITE program and would remain constant for the entire year.

As expected, even in a 4-hr test, the TCE mass removal rate was higher at the start than at the end. It is difficult to extrapolate performance over a 1-yr time period based on 4 hr and it must be expected that airborne concentrations and removal rates will gradually decrease over the year. Therefore, the reader is cautioned that the TCE mass removal rate used for this economic analysis is optimistic in assuming that it remained constant at the 4-hr rate over a 1-yr time period. In addition, the cost to remove a unit mass of TCE is considerably lower at the beginning of treatment than at the end when concentrations are lower and the distribution of the contamination among matrices may be different. Cost estimates also are provided for the subsequent aboveground removal of TCE from the extracted gas stream, although this cost varies with the concentration, scale of remediation, and method.

Costs and assumptions were based on information provided by Accutech and HSMRC, and on results and observations gained from this SITE demonstration, particularly the 4-hr postfractrure extraction test. Certain actual or potential costs were omitted because site-specific engineering aspects beyond the scope of this SITE project would be required or the item was assumed to be the obligation of the responsible parties or site owner. Cost figures provided here are “order-of-magnitude” estimates, generally +50% to -30%, and are representative of charges typically assessed to a client by the vendor.

The developer has indicated that process operation may be altered from that which was demonstrated to enhance contaminant removal, especially in the latter stages of remediation. Among these changes may be:

- repeat fracturing
- passive air inlet
- intermittent operation or pulsing
- forced hot gas injection, and
- air stripping of VOCs contained in the perched and/or groundwater, and subsequent treatment with the extracted soil vapor air stream.

The impact that these changes would have on costs has not been taken into account here.

Conclusions

- The cost to extract 1 lb of VOC measured as TCE with the Pneumatic Fracturing Extraction process assuming that the 4-hr postfracture extraction rate was maintained for 1 yr, was $140 ($307/kg). A comparison with conventional vapor extraction really should not be made since the formation is so impermeable that vapor extraction would not be practical.

- For full-scale remediation using PFE with a 500 cfm, 40 hp mobile extraction unit operating at 300 cfm, the largest cost component is labor (29%), followed by capital equipment (22%), emission treatment and disposal (19%), site preparation (1l%), and residuals/waste shipping and handling (10%). The remaining five cost categories combined accounted for the remaining 9%.

- Operational process changes to minimize residuals and waste, as suggested by the developer, may reduce costs further. These improvements were not considered.

- No cost analysis or evaluation was carried out for Hot Gas Injection since the intended source, a catalytic oxidation unit, was not employed.

Issues and Assumptions

This section summarizes the major issues and assumptions used to evaluate the cost of Accutech's Pneumatic Fracturing Extraction system. In general, assumptions are based on information provided by Accutech and observations during the demonstration project. Certain assumptions were made to account for variable site and waste parameters and would, undoubtedly, have to be modified to reflect specific conditions at other sites.

Waste Volumes and Site Size

Neither the extent of the formation to be remediated at the demonstration site nor the remediation objectives under the New Jersey Environmental Cleanup Responsibility Act (ECRA) have yet been fully determined. A pump-and-treat system probably will be used to stop the groundwater plume from migrating, but this will be inadequate or take excessively long to eliminate the ongoing contamination of the groundwater as additional contaminants seep in from the vadose zone. Conventional vapor extraction would remove the vadose zone source of the contamination, but does not appear viable for this relatively impermeable formation. Hence, PFE was considered a viable remediation alternative.

For purposes of this cost estimate, an area measuring 150 ft x 100 ft (15,000 ft^2) bordered by a fence and trees at the site was assumed to delineate the cleanup zone.

System Design and Performance Factors

A properly designed, installed, and operated vapor extraction system can remove a large amount of contamination from a site in an efficient, timely, and cost-effective manner. The three main determinants of system effectiveness are:

- the composition and characteristics of the contaminants;
- the vapor flow path and flow rate; and
- the location of the contamination with respect to the vapor flow paths.

A correctly designed and installed vapor extraction system will maximize the intersection of the vapor flow path with the contaminated zone. A correctly operated system will maximize the efficiency of the contaminant removal and reduce costs.

The number and location of extraction wells required for remediation are highly site-specific and depend on many factors, including the extent of the zone of contamination, the physicochemical properties of the contaminants, the soil type and characteristics (especially the air permeability), the depth of contamination, and discontinuities in the subsurface. The effective radius of influence is the primary design variable and incorporates many of the above parameters.

The effective radius of influence is defined arbitrarily by Accutech as the furthest extent from an extraction well at which a vacuum of 10 in. of mercury can be detected. Obviously, this definition depends on how much vacuum can be produced at the extraction well and this in turn depends on the soil characteristics. For this site, a vacuum pressure at the extraction well of 9.8 psia was assumed. Using this definition and the postfracture test results from the fracture monitoring wells, an effective radius of influence of at least 20 ft was demonstrated. For the purposes of this cost estimate, an effective radius of influence of 25 ft (area = 1964 ft^2) was assumed for the full-scale remediation. To insure that all contaminated areas are treated, the effective radius of influence of each well would have to overlap by 15 to 20%. Thus, each well would account for cleaning up roughly half of its 1964 ft^2 area or 982 ft^2. Therefore, to clean up the entire 15,000 ft^2 area of contamination, approximately 15 wells (15,000 ft^2/982 ft^2/well) would be required.

Figure A-4 in Appendix A shows a simplified flowsheet of Accutech's PFE system. A commercial-scale unit would be similar in design and performance to that demonstrated under the SITE program, but would include a larger extraction system and possibly a different well configuration.

During the SITE demonstration, average contaminant concentrations in the extracted air remained essentially the same (50 ppmv to 58 ppmv) before and after fracturing. Contaminant mass removal was enhanced by virtue of the increased air flow rate after fracturing as compared with prefracture conditions. The contaminant mass removal rate is expected to decrease with time as the site is remediated, but it was not possible to extrapolate long-term removal rates (1-yr), from short-term data (4-hr). For purposes of this economic analysis, the contaminant removal rate was assumed to be constant at a 4-hr postfracture average rate of 72.2×10^{-6} lb/min (33 mg/min) for one well operating at an air flow rate of 4.2 scfm, with all other wells capped. Similarly, where the radius of influence of adjacent wells overlap, the contaminant removal rate may be less than that observed here. For purposes of this analysis, it was assumed to be the same as that during the SITE demonstration.

As stated earlier, increasing air flow rate is the predominant way to extract gas phase contaminants from soils. The air flow rate is, in turn, determined by the vacuum pressure that can be developed at the well head, and the vacuum pressure is limited by the air permeability of the soil. For the demonstration study, a 7.7 hp blower capable of delivering a vacuum pressure of 11 psia was used, corresponding to an air flow rate up to 12 scfm after fracturing, with all other wells capped. Higher air flow rates through the formation may have been achievable if it were not for the perched water. Fluctuating perched water levels were observed to block and, after dewatering, to expose fractures. Dewatering would effectively increase the soil permeability and hence, the amount of air that could flow through the formation. In the field, it was observed that this perched water became less of a problem with time. Over the course of a 1-yr cleanup, it is reasonable to anticipate that higher flow rates could be achieved, especially with a larger blower in use.

Another way that air flow rates through the formation could be increased is by using some of the wells as passive air inlets. Limited testing during this demonstration showed that this was possible; however, the corresponding TCE concentration decreased due to dilution. The net result still was an increase in the TCE mass removal rate, although not as great as the increase in the air flow rate. This is a parameter that the developer may be able to adjust to suit a particular site to achieve optimum performance, but a larger blower would be required. For purposes of this economic analysis, an air flow rate of 20 scfm per well with all other wells capped was assumed. Hence, the total extraction rate for 15 wells would be 300 scfm, corresponding to a 30 hp blower.

The source of compressed air for fracturing would continue to be a bank of cylinders manifolded together and mounted on a mobile trailer along with a compressor that would serve to recharge the cylinder bank between fracture injections.

As mentioned earlier, perched water was an unanticipated problem encountered during the demonstration. A make-shift pumping system was installed in the field. Since similar problems may be encountered during an actual remediation, the cost of properly designing and installing a low yield pumping system was included in this economic analysis. During the SITE demonstration, the collected water was stored and shipped off-site for disposal. Recognizing that this would be very costly for a long-term, full-scale remediation, on-site treatment of the perched water along with the groundwater using an air stripper was assumed. The amount of perched water relative to the amount of groundwater is assumed to be so small that it would not add a substantial amount to the operating or capital costs of the groundwater remediation system.

The contaminants that are air stripped from the perched water can be treated with the air stream extracted from the wells. Again, this would not add substantially to the cost of the aboveground treatment of the extracted VOC vapors, which was assumed to be accomplished by carbon adsorption. Accutech has suggested that catalytic oxidation, particularly during the early periods when concentrations of stripped VOCs would be highest, would be more cost-effective. Since this approach was not evaluated during the Phase I study, it is not included in this cost analysis.

The cost estimate does not include provisions for pumping, collection, and treatment of groundwater from the saturated zone beneath the water table. Those needs are expected to be relatively constant regardless of the approach to vadose zone remediation. The duration of operation for a pump-and-treat system will be reduced by eliminating the source of contamination in the vadose zone; however, it is not possible to estimate the benefits quantitatively.

System Operating Requirements

The pilot-scale extraction unit, consisting of compressor/blower, associated piping, valving and gauges, and water knock-out vessel, was designed for the demonstration project. The compressor/blower with a capacity of 100 cfm was electrically operated and required approximately 30 amp/240V service. Air flow rate and pressure can be adjusted up to the maximum by throttling a valve. The high pressure air (up to 500 psig) for fracturing is provided by a bank of 12 cylinders. Larger fracturing and extraction systems could be designed similarly except that the compressor/blower(s) could be operated by a diesel engine or a diesel generator. Capacity would be dependent on the size of the compressor/blower selected.

Although the Pneumatic Fracturing Extraction tests were of limited duration, partially to avoid depletion of the VOCs in the formation, it can be assumed that the extraction unit would operate continuously during a full-scale remediation. Vapors would be extracted from all wells at the same time. As noted earlier, optimistic estimates were made for long term (1-yr) removal rate for VOCs based on the short term (4-hr) tests. One operator making daily visits to the site would normally be adequate to identify and correct any problems, to adjust flow rates, and, occasionally, to obtain samples from which progress could be monitored.

Utilization Rates and Maintenance Schedules

Cost for installation of wells has been separately identified at an approximate rate of $2000/well on the basis of experience at the demonstration site. This will, obviously, be dependent on the number of wells, the depth and diameter of each, and the nature of the formation.

The pneumatic fracturing portion of the process would be done at the beginning of the project and would take no more than 2 wk for all 15 wells. Again, no downtime for repairs was assumed since a back-up packer/injector would be available on-site. A 25% annual utilization rate was assumed by Accutech in estimating the capital costs for the pneumatic injection equipment.

The extraction equipment was assumed to run 24 hr/day, 350 day/yr. Since this is a continuous, steady state operation with very few moving parts after fracturing, utilization rates should be quite high once operating parameters have been established. A 90% on-line stream factor was assumed. One week for mobilization and training and 2 wk for demobilization were included in the 1 yr on-site time.

Routine maintenance for all of the equipment would be rather straightforward and could be done while in operation.

Financial Assumptions

For the purpose of this analysis, capital equipment costs include profit, overhead, and maintenance and were amortized by the developer over a 2-yr period with no salvage value. Insurance and tax are assumed to be fixed costs listed under “Startup” and are calculated as 10% of annual capital equipment costs.

Basis for Economic Analysis

In order to compare the cost-effectiveness of technologies in the SITE program, EPA breaks down costs into 12 categories using the assumptions already described. The assumptions used for each cost factor are described in more detail below.

Site Preparation Costs

The amount of preliminary preparation will depend on the site and should be minimal when compared to other remediation approaches. Site preparation responsibilities include site design and layout, surveys and site logistics, legal searches, access rights and roads, and preparations for support facilities, decontamination facilities, utility connections, and auxiliary buildings.

Drilling and preparation (purging, casing, caps, etc.) of fracture/extraction wells are assumed to be performed by a contractor and are a necessary part of the technology. Although the total of these costs are highly site-specific, they are included at a rate of $2000/well. For 15 wells, the total for drilling would be $30,000. The costs of other wells, such as those for site characterization and SITE project monitoring of the process, are not included.

Additional costs incurred under the SITE program that would also be included in a full-scale remediation would be:

	SITE	Full-Scale
Fencing	=$1000	$2000
Electric Service Connection Charge	=$2000	$2000
Electric Panels and Outlets	=$3000	$3000
Cleaning Debris, Putting Gravel on Permeable Fabric	=$2000	$5000

Permitting and Regulatory Costs

These costs may include actual permit costs, system health/safety monitoring, and analytical protocols. Permitting and regulatory costs can vary greatly because they are very site- and waste-specific. For example, in the case of the demonstration site, the bulk of the permitting efforts are part of the more extensive ECRA Cleanup Plan, an effort that has been ongoing for some time and which addresses many aspects beyond remediation of the vadose zone. New Jersey did, however, require a Permit to Construct and Operate an air emission source ($1,000) and permits for each well ($50/well x 15 wells = $750). No other permitting costs are included in this analysis; however, depending on the site, this could be a significant factor since permitting can be a very expensive and time-consuming activity. The total for Permitting and Regulatory Costs would be $1,750.

Equipment Costs

Capital equipment costs were apportioned into vapor extraction and pneumatic fracturing components. The vapor extraction equipment cost of $1,090/wk was provided by Accutech Remedial Systems, Inc. and included a mobile trailer equipped with a 40 hp vacuum blower, associated plumbing, controls and instrumentation, and a water knock-out vessel. Capital equipment costs for the same sized unit from several independent sources averaged about $50,000, instead of the $113,360 estimated for Accutech's proprietary equipment. The developer has, however, decided to amortize these costs in a relatively short time period (2 yr) and to include profit, overhead, and maintenance, which translates into a capital equipment cost of $113,360.

The pneumatic injection equipment cost of $7,131/wk was provided by HSMRC and included a mobile trailer equipped with a bank of 12 cylinders manifolded together, and maintained at a pressure of 2,500 psig with a 12 hp, 5,000 psig compressor to recharge the cylinder bank in 45 min between fracture injections, two packer/injector assemblies (one for standby), and associated plumbing, instrumentation and controls. An additional $6,656/wk is included for a monitoring and analytical package, including an on-site gas chromatograph and associated power supplies, data acquisition, computer, software and peripheral support. The pneumatic fracturing equipment portion of the cost would then add up to $l3,787/wk.

For a 1-yr remediation, the total equipment cost can be calculated as:

Vapor Extraction:	$1,090/wk	x 50 wk	=	$54,500
Pneumatic Fracturing:	$l3,787/wk	x 2 wk	=	27,574
				$82,074

Since no attempt was made in this project to estimate the total. VOC's in the vadose zone, it is not possible to estimate the long term capital cost contribution to overall cost. Instead, for planning purposes, it is assumed that the TCE removal rate remains constant for a I-yr period during which time the site is remediated to a level (TCE residual concentration in air, soil gas, or soil) acceptable to the New Jersey DEPE. The reader is cautioned to use these numbers with great care due to the assumptions made.

Startup

The mobile unit is designed to be moved from site to site. Transportation costs are only charged to the client for one direction of travel and are usually included with mobilization rather than demobilization. Transportation costs are not expected to be a major factor; they are variable and dependent on site location and size/weight load limits, which vary from state to state.

The amount of on-site assembly required for the mobile unit (or a permanent installation) is minimal, consisting of unloading equipment from trucks and trailers used for transportation; joining piping to well caps, the extraction blower, and the carbon adsorption system; and assuring that all joints are leak-free. Mobilization and minimal training are estimated to take one person about 1 wk; this time is included in the total time on-site (1 yr).

It is anticipated that installation of wells would be done before and during the mobilization of the fracturing/extraction system, based on careful review of existing site characterization data. This also would be the basis for selecting PFE as the preferred remediation technology. Well installation would be carried out by a drilling contractor, but it would presumably require oversight by one person. Assuming one well could be drilled and cased per day, this could add an additional 2 wk of effort to install 15 fracture/extraction wells. Fracturing also would be integrated into the drilling time frame.

Depending on the site and the contaminants, local authorities may impose specific guidelines for health and safety monitoring programs. The stringency and frequency of monitoring required may impact on project costs, for example, if Level C protection is required during well drilling or during fracturing to protect against inadvertent emissions resulting from vertical fractures.

Fixed costs, such as insurance and taxes are also included here. The total of all startup costs was assumed to be 10% of the annual capital equipment costs, or $8,200.

Labor

Operating labor costs were also divided into vapor extraction and pneumatic fracturing components. Accutech Remedial Systems, Inc. assumed that one engineer at a salary of $65/hr would devote 24 hr/wk for 49 wk/yr to vapor extraction, for a total of $76,440. During mobilization and demobilization, Accutech assumed that two engineers would work 40 hr/wk (1 wk for mobilization, 2 wk for demobilization), for an additional cost of $15,600. HSMRC assumed three engineers at a salary of $65/hr would work 40 hr/wk for 2 wk/yr on pneumatic fracturing for an additional cost of $15,600. No labor cost has been included for site characterization or system design.

The hourly rate includes salary, benefits, and profit but excludes administration and overhead costs. Travel, per diem, or car rental have not been included in these figures and can easily have a major impact if the duties cannot be assumed by an on-site employee. The total cost of labor for a 1-yr remediation is then $107,640.

Consumables and Supplies

Compressed air is the major consumable used by the PFE process. For the demonstration, it was furnished by a bank of compressed air cylinders. For a fill-scale remediation requiring numerous fracturings, an on-site compressor was deemed to be more economical, even though it is used only to repressurize a bank of cylinders. These costs have already been discussed under "Equipment Costs".

Some lubricants are required to maintain the blowers but the cost would be negligible. No chemicals are used in the process.

Where carbon adsorption is used to collect the VOCs removed from the extracted gas, the cost of this material, together with disposal cost, must be included. For this estimate, that cost is included under "Emission Treatment and Disposal".

Two other items that should be considered are health and safety gear, estimated at $1000/yr, and maintenance supplies (spare parts, oils, and lubricants, etc.), estimated at $3000/yr by ARS. This may be somewhat higher during well installation when events of elevated VOC levels in the air may be encountered and for which protection should be worn as a precaution. Nevertheless, since the manpower requirements for operating the system are small, the cost for health and safety gear will be minimal.

Utilities

The total electrical demand for operation of the system is estimated to be about 30 hp, primarily to operate the vacuum blower. Assuming continuous operation, electrical cost of $0.06/kwh would equate to about $11,750 per year. The cost of bringing power to the site (approximately $2000 at the demonstration site) has been included under "Site Preparation." It is assumed that the cost for diesel fuel for larger, diesel operated compressors would be comparable.

A small additional cost could be included for lighting of the system during the nights, if only for security purposes. Including on-site telephone and facsimile service, the total annual utility costs would be about $17,000/yr.

Emission Treatment and Disposal

The extracted VOCs from the Pneumatic Fracturing Extraction will require collection and treatment. Although Accutech has proposed catalytic destruction, particularly where VOC concentrations in the extracted air are above approximately 50 ppmv, carbon adsorption was used for control of these emissions during the demonstration.

For the full-scale remediation, it was assumed that the TCE concentration remains at 50 ppmv for the full 1 yr duration at an air flow rate of 300 scfm. Thus, 1210 kg or 2660 lb of TCE would be removed. If it is conservatively estimated that 10 lb of carbon are required for each pound of VOC extracted, then 26,600 lb of carbon would be necessary for treatment over the year.

Rental of a stainless steel vessel with 1800 lb of vapor phase reactivated carbon would cost about $4,500/unit, including spent carbon handling and off-site reactivation. The unit would have to be replaced 15 times over the course of a year. Additionally, there would be a one time RCRA carbon acceptance fee of $2,500 to sample the spent carbon to ensure safe reactivation. Therefore, it would cost about $70,000/yr for emission treatment and disposal.

Residuals Storage, Handling, and Transport Costs

At the demonstration site, the ECRA Cleanup Plan calls for pump-and-treat of the contaminated groundwater at the site. Costs for this activity are not included in the estimate. At other sites, such pump-and-treat operations may be necessary or desirable as a means of suppressing the groundwater table to create an “artificial” vadose zone or to remove dissolved contaminants before the PFE process is applied. In those cases, an additional cost factor may need to be included. Further, although the Cleanup Plan calls for carbon treatment of the contaminated groundwater at the demonstration site, air stripping of contaminated water and catalytic destruction of the stripped VOCs along with the VOCs removed by vapor extraction may be a preferred alternative at other sites.

The perched water found at the demonstration site presented an unanticipated process and disposal problem and a makeshift pumping system was installed to remove water from the well bores. A similar perched water problem may be encountered at other sites. Hence, the cost of designing, buying, installing, and operating a comparable system was included. It was assumed that a low yield (3 gpm) pneumatic pump would be installed at each of the 15 wells. The cost, including the associated controls, plumbing, and compressor, was estimated to be $20,000.

During the demonstration, -4000 gal of water pumped from the vadose zone was stored in 55 gal drums, transferred to a 5000 gal tanker truck, analyzed, and disposed of as hazardous waste. Rental of a 5,000 gal tanker truck was $1,200/mo. Sampling, analysis, and disposal cost an additional $3,400. It was unclear whether the water required disposal as a hazardous waste. For a full-scale remediation, it would be cost-effective to airstrip contaminants from the perched water together with the groundwater and treat the contaminated air stream with carbon. The treated water would then be disposed of to a POTW or surface water. Since, as noted earlier, the incremental cost for air stripping of the perched water is expected to be minimal, no additional cost for storing or disposing of the perched water was included.

During the SITE demonstration, 18 drums of well cuttings from 14 wells (8 FMWs, 2 injection wells, and 4 TMWs) were generated. The cost to manifest, transport, handle, and dispose of these was estimated at $500/drum. Since a full-scale remediation will involve about the same number of wells, it was assumed that 20 drums of well cuttings would be produced. The cost to dispose of these was then estimated to be approximately $10,000.

Two drums of health and safety gear were produced during the SITE demonstration and the cost to manifest, transport, handle, and dispose of these was estimated at $600/drum. For a full-scale remediation, it was assumed that 1 drum of personal protective equipment would be generated every month. Therefore, the annual cost to dispose of 12 drums would be $7,200 (12 drums x $600/drum).

Therefore, the total yearly cost of Residuals/Waste Storage, Handling, and Shipping are itemized as follows:

Dewatering System:	$ 20,000
Well Cuttings:	10,000
Personal Protective Equipment:	7,200
TOTAL	$ 37,200

Analytical Services

Standard operating procedures for Accutech do not require planned sampling and analytical activities; in practice, routine monitoring of extracted VOCs might be carried out using portable instruments such as the HNu or OVA, with less frequent but more complete laboratory analyses by GC or GC/MS for confirmation and/or to meet regulatory requirements. Short term rental of a portable unit (OVA or HNu) is approximately $250/month and is assumed to be included in “Capital Equipment” costs. No costs have been included for pre-disposal testing of wastes.

Facility Modification, Repair, and Replacement

As stated earlier, site preparation activities for the demonstration were carried out by EPA under the SITE contract. Likewise, any modifications to the site for a more extensive remediation, such as leveling, excavation, removal of pipelines, sealing of pre-existing wells, etc., were assumed to be done by the responsible party (or site owner), but such activities might be carried out by a contractor such as Accutech and have already been included under Site Preparation.

Demobilization

It is estimated that demobilization would take about 2 wk. Site cleanup and restoration is limited to the removal of all equipment, facilities, and wastes from the site. Requirements for grading or recompaction of the soil will vary depending on the future use of the site and is assumed to be the obligation of the responsible party or site owner. Demobilization of wells is a requirement of New Jersey well drilling permits. It consists of removing aboveground casing, plugging the full length of each well with grout or cement, and surveying each well.

Since the wells at the demonstration site may be used in the coming years as part of the remediation, responsibility for ultimate demobilization (abandonment) was transferred from EPA to McLaren/Hart, the site owner's environmental consultant. The cost for well closure was estimated at $100/well or $1,500 for 15 wells.

Results

Table 5 shows a breakdown of the costs for one possible configuration of a full-scale remediation of a given portion of this site using the PFE process. The largest cost category is Labor (29%), followed by Capital Equipment (22%), Emissions Control (19%), Site Preparation **(1** 1 %), and Residuals/Waste Shipping, Handling and Storage (10%). The remaining five cost categories account for the remaining 9%. The reader is cautioned to view the figures carefully when applying them to other sites.

Table 5. Estimated Annual Costs for large Scale Cleanup

Cost Category	Total Cost	Percent of Total
Site Preparation (leveling, wells)	$ 42,000	11.3
Permitting and Regulatory Requirements	1,750	0.5
Capital Equipment (amortized over 2 yr)	82,074	22.1
Startup	8,200	2.2
Labor - Salary	107,640	29.0
Consumables & Supplies	4,000	1.1
Utilities-Electricity, Telephone, Fax)	17,000	4.6
Emission Treatment and Disposal	70,000	18.8
Residuals Storing, Handling, and Transport	37,200	10.0
Analytical Services	N/A	----
Facility Repair, Replacement & Modification	N/A	----
Demobilization	1,500	0.4
TOTAL	$371,364	100.0

Assuming the contaminant removal rate to be constant at the 4-hr postfracture extraction rate of 72.2 x 10" lb/min for the entire 1-yr period, the average unit cost of TCE removal will be $371,364 for 1,210 kg (2,660 lb) of TCE, or $307/kg ($140/lb) of TCE. It is felt that this is a valid, but not necessarily realistic, number, considering the optimistic assumptions regarding TCE removal rate.

Other operating scenarios are obviously possible. For example, a more realistic approach could be to assume that the TCE removal rate decreases linearly over the year by 90%, rather than remaining constant. The average removal rate then would be 55% of that used in the above estimate. Examining the 12 cost categories, however, only VOC control cost would be impacted. Consequently, the total cost for a I-yr cleanup would be $339,864. Since only 665 kg (1460 lb) of TCE would be removed, the unit cost would increase to $5 1 l/kg or $232/lb of TCE removed.

Similarly, if the original hypothetical mass of TCE, 1210 kg, were removed over a 2-yr cleanup, the total cost would increase to about $534,164 and the unit cost would be $443/kg or $20l/lb of TCE removed. These figures assume increases of $56,680 in capital, $5,670 in startup costs, $81,120 in labor, $4,000 in consumables, and $17,000 in utilities for the second year of operation.

Section 5
Bibliography

K. G. Angell, Bass, D. H., and Herman, C., "Air Sparging: An Innovative Technique for Site Remediation," Proceedings for the 18th Environmental Symposium and Exhibition, American Defense Preparedness Association, Alexandria, VA, February 24-27d, 1992, p. 57-63.

Anon, "Pneumatic Fracturing Unlocks Trapped Soil Contaminants, Enables In Situ Remediation," Chemical Engineering Progress, Oct., 25-26 (1992).

Anon, "Soil Cleanup Method Being Developed," Chem. & Eng. News, Sent. 21, 17 (1992).

0. Cunha-Leite, "Incineration of Liquid Halogenated Hydrocarbons," The National Environmental J., Sent./Oct., 38-42 (1992).

R. R. DuPont and Reineman, J. A., "Evaluation of Volatilization of Hazardous Constituents at Hazardous Waste Land Treatment Sites," U. S. Environmental Protection Agency, Ada, OK, EPA/600/2-86/07 August 1986.

N. J. Fendinger, Glotfelty, D. E., and Freeman, H. P., "Comparison of Two Experimental Techniques for Determining Air/Water Henry's Law Constants," Environ. Sci. & Tech., 23 #12, 1528 (1989).

C. Y. Jeng, Chen, D. H., and Yaws, C. L., "Data Compilation for Soil Sorption Coefficient," Pollution Engineering, June 15, 54-60 (1992).

P. Kroopnick, "Modeling the In Situ Venting of Hydrocarbon Contaminated Soil," Proceedings for the 18th Environmental Symposium and Exhibition, American Defense Preparedness Association, Alexandria, VA, February 24-27, 1992, p. 410-419.

McLaren/Hart Environmental Engineering Corp., "Cleanup Plan for Groundwater - Derelco Properties - Hillsborough, New Jersey," October, 1990.

McLaren/Hart Environmental Engineering Corp., "Groundwater Sampling Plan Results Report - Derelco Property, Hillsborough, New Jersey," October, 1990.

McLaren/Hart Environmental Engineering Corp., "Interim Pre-Design Report: Groundwater Cleanup - National Diagnostics and Derelco Property - Somerville, New Jersey," December, 1991.

J. R. Schuring and Chan, P. C., "Removal of Contaminants from the Vadose Zone by Pneumatic Fracturing," U. S. Geological Survey, Dept. of Interior, Award 14-08-0001-G1739, January 1992.

J. R. Schuring, et al, U. S. Patent 5,032,042, "Method and Apparatus for Eliminating Non-naturally Occurring Subsurface, Liquid Toxic Contaminants from Soil," July 16, 1991.

C. C. Travis and MaCinnis, J. M., "Vapor Extraction from Subsurface Soils. Is it Effective?" Environ. Sci. & Tech., 26, #10, 1885-1887 (1992).

U. S. Environmental Protection Agency, "Guidance on Remedial Actions for Contaminated Ground Water at Superfund Sites," U. S. Environmental Protection Agency, Washington, D.C., EPA/540/G-88/003, December 1988.

U. S. Environmental Protection Agency, "Technology Evaluation Report: SITE Program Demonstration Test; Terra Vac In Situ Vacuum Extraction System - Groveland, Massachusetts," U. S. Environmental Protection Agency, Cincinnati, OH, EPA/540/5-89/003a, April 1989.

U. S. Environmental Protection Agency, "Guide for Conducting Treatability Studies Under CERCLA: Soil Vapor Extraction - Interim Guidance," U. S. Environmental Protection Agency, Cincinnati, OH, EPA/540/2-91/019A, September 199 1.

U. S. Environmental Protection Agency, "Seminar Publication: Site Characterization for Subsurface Remediation," U. S. Environmental Protection Agency, Cincinnati, OH, EPA/625/4-91/026, November 1991.

U. S. Environmental Protection Agency, "PROJECT SUMMARY: A Technology Assessment of Soil Vapor Extraction and Air Sparging," U. S. Environmental Protection Agency, Cincinnati, OH, EPA/600/SR-92/173, September 1992.

Appendix A
Process Description

Introduction

Vapor extraction is becoming a widely accepted technique for the removal of volatile organic compounds from unsaturated ground formations. As an "in situ" technology, at least to the extent that excavation is not required, it offers considerable cost savings over soil excavation and aboveground treatment or off-site disposal. The primary limitation to the technology is that the vadose zone formation must be sufficiently permeable for air to flow and vaporize the volatile contaminants into the air stream.

This section of the report presents a concise description of the Pneumatic Fracturing Extraction (PFE) and Hot Gas Injection (HGI) processes as they were carried out at the demonstration site in New Jersey. Pre-demonstration factors involved in site selection are presented to assist engineers and scientists in evaluating the suitability of the process for their own needs at Superfund and other hazardous waste sites. Results of the demonstration, including a summary of analytical data, are presented in Appendix C. More comprehensive descriptions of the process and the demonstration study are contained in the Technology Evaluation Report.

Vapor extraction can be carried out in one of several modes, including:

a. vacuum extraction from a central well (or wells) with air injection into surrounding wells;

b. vacuum extraction from a central well (or wells) with surrounding wells open to the atmosphere (passive inlet);

c. vacuum extraction from a central well (or wells) with no surrounding wells or with surrounding wells sealed;

d. air injection into a central well with vacuum extraction from surrounding wells; and

e. combinations of the above.

Varying combinations of the above modes were examined during this demonstration.

Process Description

To facilitate the cleanup of soil and rock formations with poor air permeability, such as shales and clay, Accutech and the Hazardous Substance Management Research Center (HSMRC) at the New Jersey Institute of Technology have devised a means of increasing the permeability of such tight formations. This method, the subject of this investigation, involves injecting short bursts (<1 min) of compressed air (up to 500 psig) into the formation, causing the formation to fracture at weak points. These fractures, which are found to occur predominantly in the horizontal direction in formations such as clay and shale, enlarge and extend existing fissures and/or generate new fissures. Where these fractures connect an extraction well with an air injection well or other source of air, they allow increased flow of air through the formation and, in effect, increase the permeability of the formation. The increased flow of air then allows increased masses of trapped/adsorbed/absorbed organics to be removed by volatilization. In addition, the generation or extension of fractures can provide access to areas of the formation that were simply not accessible to extraction before fracturing. See Figure 1, shown earlier, for a conceptual representation of the effect of fracturing on a formation of low permeability.

For maximum control, the fracturing is carried out in narrow depth intervals using a proprietary lance (HQ Injector) equipped with rubber "packers" which, are expanded by pressurization with air to isolate each interval of the wellbore from those above and below it. This tends to concentrate the effect of the pressure pulse and may also help minimize the formation or propagation of vertical fractures by providing resistance above and below. The injector and packer are shown schematically in Figure A- 1.

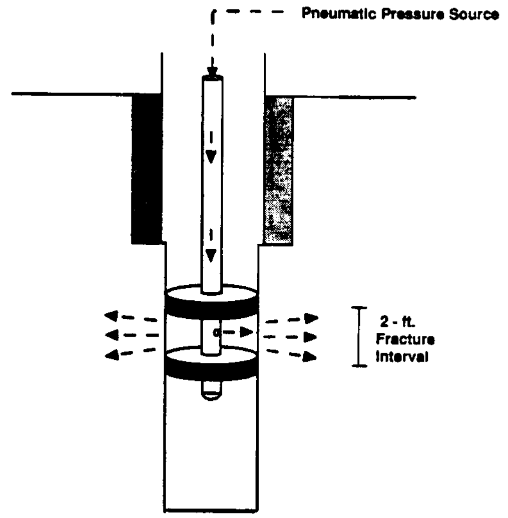


Figure A-l. HQ Injector.

Once fracturing has been successfully achieved in several intervals, the permeability of the formation is significantly increased and the radius of influence for vapor extraction is expanded. In situ removal of VOCs then can be accomplished.

By enlarging the radius of influence, fracturing allows vapor extraction with a minimal number of wells and/or increased effectiveness. At the demonstration site, the radial distribution of fractures was relatively uniform, but fracturing is influenced by the geological character of the formation and the presence of easy paths, such as pipelines, obstacles, perched water, or building foundations. Consequently, the actual radial impact may not be uniform. Even heavy loads on the surface may prevent or reduce fracturing in particular directions, a phenomenon used to advantage when oil wells are hydraulically fractured at much greater formation depths. By carefully monitoring the direction and distance (radius) of fracturing using measurements of surface heave and connectivity between wells, an entire formation can be remediated more efficiently, with a minimum number of wells, and in a shorter time period.

Accutech also has proposed that hot gas injection into bedrock can accelerate VOC removal by vapor extraction, particularly when integrated with PFE. Hot Gas Injection was an outgrowth of plans (not yet implemented) to destroy extracted chlorinated VOCs with a catalytic oxidation unit and inject the hot exhaust gases from the catalytic oxidation unit. For the current Phase I demonstration, hot gas production was simulated by compression of air, albeit at a significantly lower temperature (~200°F to 250°F) than expected from the catalytic oxidizer (-1000°F). In addition to providing a preliminary evaluation of the technique, these data are being used by HSMRC in developing and calibrating a thermal model for hot gas flow and heat transfer in different formations.

Several experiments were devised to evaluate the PFE technology and its applicability to this site. A series of 6-in. diameter monitoring wells surrounding a central fracturing well of 3 in. diameter were installed, each limited to a depth of about 20 ft below land surface (bls) to assure that the water table was not penetrated. Each well, originally drilled out to 10 to 12 in. in diameter to a depth of about 8 ft, was cased to about 8 ft bls with a 6 in. OD steel casing threaded at the top. The remaining length of each well was left uncased and unscreened to assure maximum connection with the formation. Each well casing was fitted with a threaded iron cap with two 2-in. ports (Figure A-2) where the extraction hose, a gauge, manifold, injection, or extraction equipment could be installed (Figure A-3).

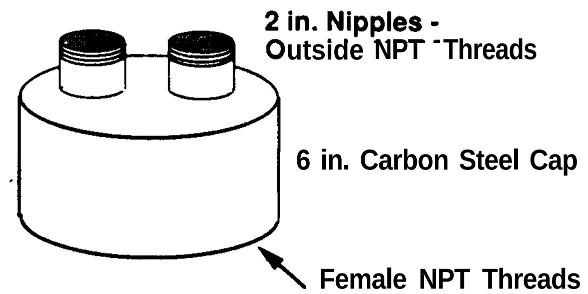


Figure A-2. Wellhead design.

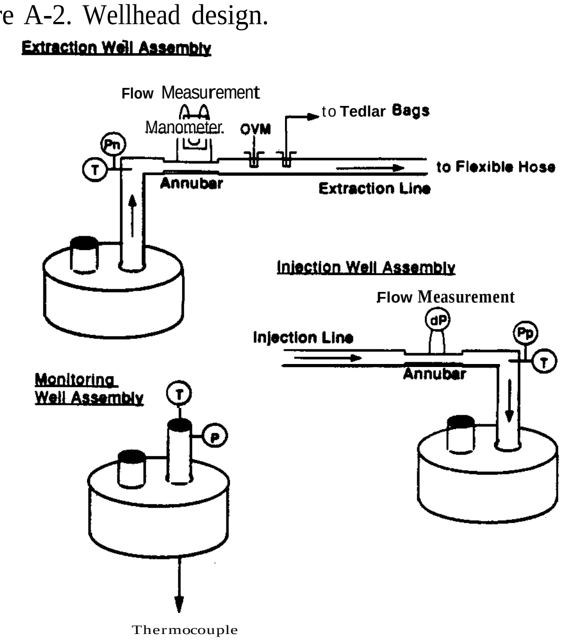


Figure A-3. Wellhead assemblies,

The vacuum extraction system used in this demonstration consisted of a single trailer (8 ft by 15 ft) on which the compressors, manifold (with valves and gauges), water knock-out vessel, and compressor/vacuum blowers were installed (Figure A-4). Two granular activated carbon adsorption drums (55 gal) were installed in series to remove the VOCs from the extracted air before it was exhausted to the atmosphere. The pneumatic injection system consisted of the HQ Injector connected to a bank of compressed air cylinders through a manifold and an electrical solenoid valve that allowed a high, controlled pressure (up to 500 psig) to be introduced into the interval when activated. Once fracturing was completed successfully in all intervals, as indicated by pressure/flow measurements at the fracture well indicative of connection between wells, and surface heave measurements by electronic tiltmeters and other instruments, the system was ready to operate as a conventional vapor extraction unit. For the primary tests of the demonstration, the central or fracture well became the extraction well while air was drawn in from the surrounding formation, with all monitoring wells capped, or by opening one or more monitoring wells to allow passive air inlet. Well placement for the demonstration is shown in Figure A-5.

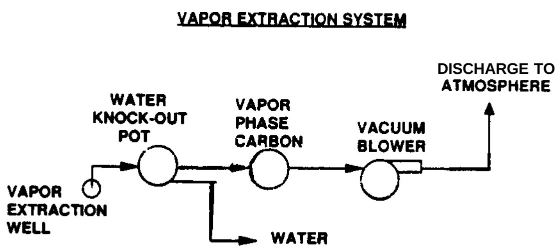


Figure A-4. Vapor extraction system.

A level area about 50 x 50 ft is needed to support the extraction trailer, the compressed air source, and auxiliary facilities. The capacity of the compressor used in the demonstration was about 100 cfm at a maximum extraction vacuum of about 10 psia.

For the demonstration of PFE, the series of experiments included:

a. Measurement of pressure, air flow rate, and TCE concentrations in 4-hr tests before fracturing, after a 24-hr dormant period, and after fracturing, using the fracture well as a central extraction well with all other wells capped;

b. Measurement of pressure, air flow rate, and TCE concentration at the central fracture/extraction well before and after fracturing, with some monitoring wells open for passive air inlet;

c. Measurement of air flow rate and pressures while extracting at individual monitoring wells with all other wells capped, both before and after fracturing;

d. Measurement of pressure, air flow rate, and TCE concentrations before and after each 2-ft interval was fractured to establish whether fracturing of that interval had been successful.

During the Hot Gas Injection tests, compressor exhaust air (-200°F to **250°F)** was injected at between 15 and 24 psia and 75 scfm into one well while temperature was monitored in all wells and the extracted air flow rate and TCE concentration were measured in the extraction stream manifold. Extraction tests were also conducted prior to the start of the HGI experiments for comparison purposes.

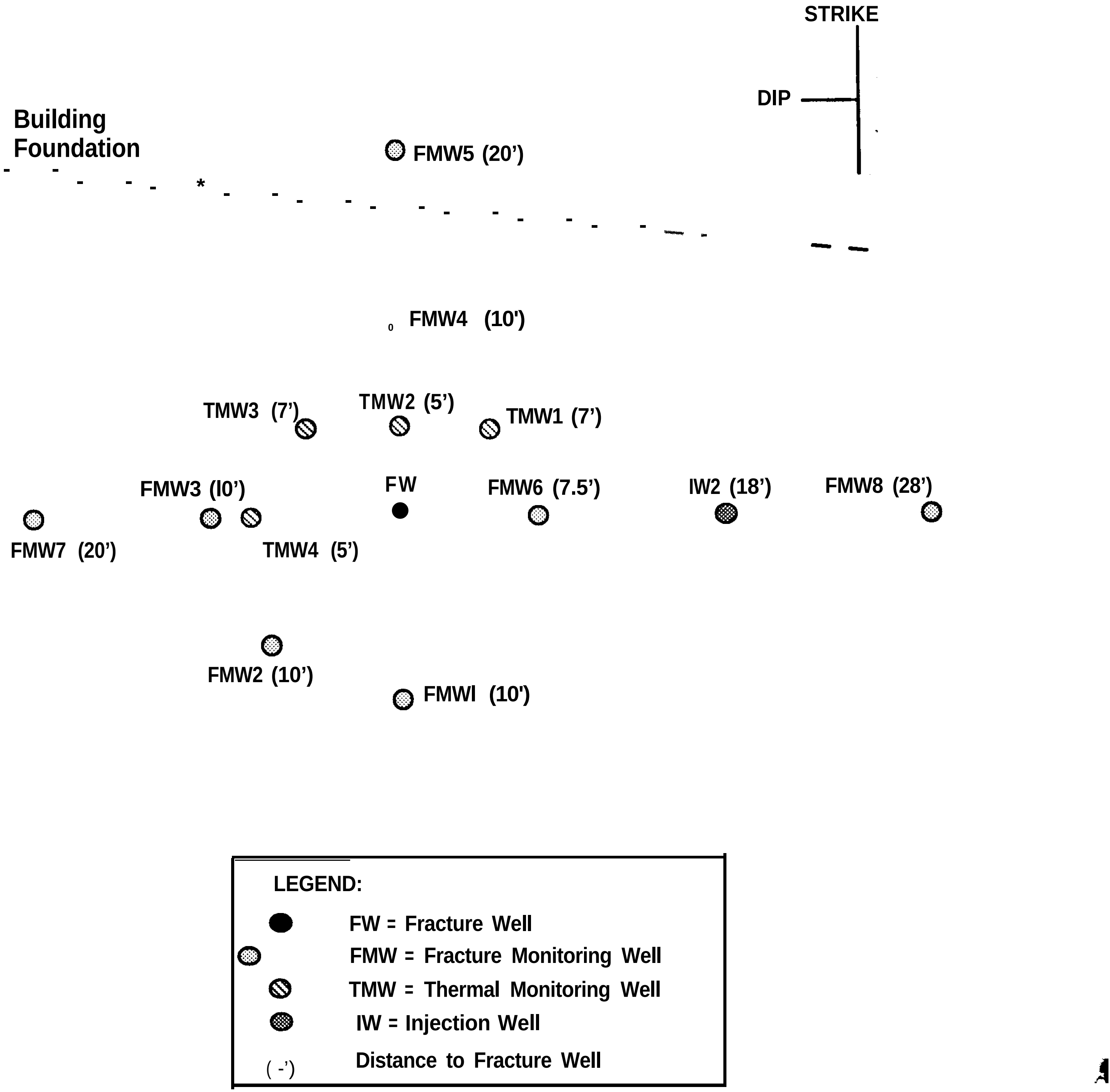


Figure A-5. Well location diagram.

Appendix B
Vendor's Claims for the Technology

Technology Overview

Conventional in situ soil vapor extraction (SVE) is a remediation treatment technology that is finding widespread use for the removal of volatile organic compounds (VOCs) in the vadose zone. By simply extracting and treating contaminated air from the subsurface, a formation can be cleaned up relatively quickly and efficiently. However, a major obstacle to this form of remediation is formation permeability. Low permeability formations, such as fractured shales, silts, and clays, usually do not allow sufficient subsurface air flow for conventional vapor extraction to be effective. Thus entire pockets of VOCs may remain unaffected by remedial attempts while continuing to slowly contaminate ground-water. Pneumatic Fracturing Extraction SM (PFE)SM, however, is a treatment process developed by Accutech Remedial Systems, Inc. to overcome the difficulties of low permeability formations and to allow thorough and effective in situ remediation.

An integral component of the PFE technology is a patented (U.S. Patent # 5,032,042) process called Pneumatic Fracturing, which was developed by the Hazardous Substance Management Research Center (HSMRC) located at the New Jersey Institute of Technology. Accutech is a technology development partner with the Center and is currently the only company permitted to apply this patented innovative technology in the United States. Accutech's integration of the pneumatic fracturing technique with other in situ treatment methods allows for cost effective treatment of a wide range of contaminant compounds in complex geologic matrices.

With the PFE process, the difficulties posed by low permeability formations are overcome. During the SITE Demonstration, increases in permeability were tabulated by measuring the increase in air extraction flow rate obtained from the formation. Demonstration results indicated extraction flow rate increases of up to 19,500% and TCE mass removal rate increases of about 2,300%. In other types of formations, even greater increases have been recorded.

The increase in extraction air flow rate provided by PFE is significant in that it means that a greater amount of air is moving through the formation at a given time. Better subsurface air flow will allow contaminants to volatilize and be removed faster than with conventional technology.

The formation permeability increase created by PFE also allows for a much greater vacuum radius of influence to be induced from an extraction well. During all Demonstration postfracture extraction tests, communication between the monitoring wells and the fracture well had vastly improved due to the PFE.

The most graphic way to quantify the overall effect is through a vacuum radius of influence contour profile. Figures B-l and B-2 represent the effective areas of influence for the prefracture and postfracture conditions, respectively. By selecting the 13 in. (of water) vacuum as the outer boundary of influence, the effective radius of influence was increased from 557 ft^2 to 1488 ft^2, almost a three-fold increase. It should be noted that the postfracture value was extrapolated beyond monitoring well FMW5 because this well represented the most distant monitoring point. As supported by the very high vacuum gradient measured at FMW5, the area under effective vacuum influence may have been significantly greater but could not be measured.

Since the spacing between extraction wells is significantly increased, the total number of wells needed to remediate a site is reduced. As a result, contaminants are extracted faster and from a larger subsurface volume than was initially possible, at a substantial cost savings to the client.

Theoretical Discussion of Pneumatic Fracturing Extraction

Fracture orientation is an important consideration in the application of Pneumatic Fracturing Extraction for full-scale remediation projects. Both horizontal and vertical effects were studied carefully during the Demonstration.

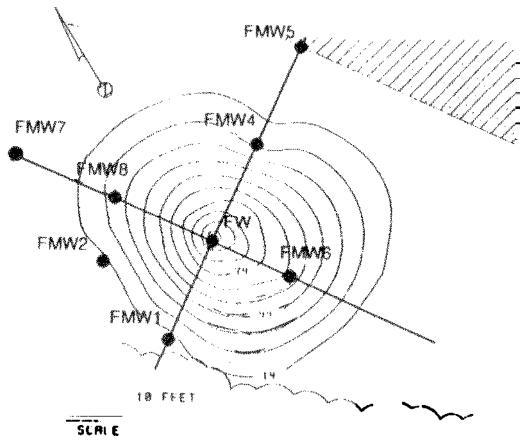


Figure B-l. Prefracture vacuum radius of influence.

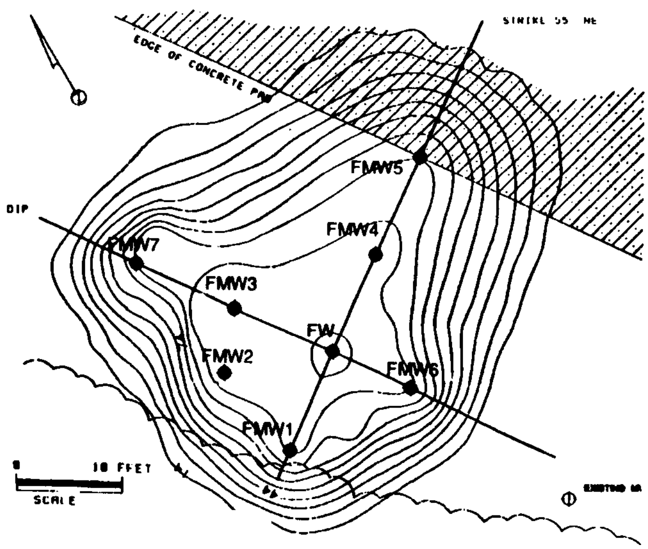


Figure B-2. Postfracture vacuum radius of influence.

Fracture Orientation-Horizontal Effects

Several independent field observations confirmed that the direction of fracture propagation at this site was predominantly horizontal. This was expected since the nearly horizontal bedding joints in the bedrock provided preferential planes of weakness. Another factor which probably affected fracture orientation was the overconsolidated condition of the bedrock formation. Horizontal fractures are favored in overconsolidated formations since the direction of the least principal stress is vertical and the formation separates in a sheet-like fashion when subjected to injection pressures. Although no measurement of in situ stresses was made at this site, regional geologic data suggest that this formation is typically overconsolidated at shallow depths.

Direct evidence of horizontal fracture orientation was provided by electronic tiltmeters, which showed circular or elliptical patterns of surface heave extending 25 ft and more from the injection point. Based on general experience in the petroleum industry with hydraulic fracturing, this pattern of surface deformation is consistent with a horizontal fracture plane. In contrast, the surface heave pattern for a vertical fracture plane would have been "saddle shaped", which was not observed during any of the injections. Additional evidence of horizontal fracturing was provided by the strong air communication observed between the fracture well and the seven outlying monitoring wells. All of the monitoring wells, which ranged from 7.5 to 20 ft from the fracture well, showed positive pressure surges during injection which could only have been caused by horizontal fractures intersecting the wells.

Fracture Orientation- Vertical Effects

It is believed that vertical fracturing at this site was minimal, since a formation does not yield along two perpendicular planes simultaneously. Some dilation of existing vertical fractures above the injection zone probably occurred as rock blocks shifted during injection. While it is difficult to determine whether or not any new downward vertical fractures were caused by the pneumatic injections, the continued presence of perched water in the treatment zone throughout the demonstration suggests that downward vertical fractures did not form. If they had, the perched water would have drained after completion of the fracturing operation.

Fracture Control and Uniformity

The geologic structure of the site can influence the propagation of pneumatic fractures. As a result, fracture patterns (when viewed in plan) are not always circular, but may exhibit some directional preference. In sedimentary rock formations, for example, pneumatic fractures will typically propagate along the bedding planes. In tilted sedimentary beds, the dip and strike may also be significant, since in situ stresses and secondary jointing systems usually align relative to these directions. Directional fracture preferences at sites are identified during pilot testing and are incorporated into the design of the production fracturing operation.

PFE injections are typically accomplished using a proprietary HQ injector which evenly distributes the air in all directions simultaneously. A modification of this injector can encourage fracture propagation towards a particular direction. Steering of fractures can also be accomplished by positioning a surface load adjacent to the injection hole, which is a technique used in the hydraulic fracturing industry.

The *Self-Propping Phenomenon*

Following pneumatic injections, the formation settles and the fracture network constricts. Field data indicate that the closure of fractures is only partial, however, as residual surface heave was recorded by both tiltmeters and optical levels at the SITE Demonstration. The formation clearly exhibited the phenomenon known as "self-propping". This behavior is attributed to the asperities present along the fracture planes, as well as the rock block shifting which takes place during injection. Self-propping is accentuated in brittle geologic materials like the siltstone present in the fracture zone at this site.

Once formed, the open, self-propped fractures resulting from the pneumatic injections are capable of transmitting significant amounts of fluid flow. The high flow potential for even small fractures may be explained by the "cubic law", which states that flow rate in planar fractures is proportional to the cube of the aperture. Numerous hydrogeologic studies have confirmed the cubic law prevails in fractured bedrock formations, and this is the principal reason why dramatic permeability increases are observed in pneumatically fractured formations.

Diffusion and Flow Channelization

Once a fracture network is established in a low permeability formation, aqueous and residual products in the vicinity of the fracture are easily accessed, and in the case of PFE, they are removed rapidly through volatilization. It is expected that the fracture distribution in a formation will not be totally uniform, since certain geologic conditions will possess preferential directions. In sedimentary rock formations, for example, pneumatic fractures will typically propagate along the bedding planes. In tilted sedimentary beds, the dip and strike may also be significant, since in situ stresses and secondary jointing systems usually align relative to these directions. Directional fracture preferences at sites are identified during pilot testing, and are incorporated into the design of the production fracturing operation.

It is noted that highest contaminant concentrations usually occur within and adjacent to existing structural discontinuities in the formation (e.g. joints, cracks, bedding planes). Since pneumatic fracturing dilates and interconnects existing discontinuities, direct access is provided to a majority of the contaminant mass. In these situations, the diffusive processes in the matrix blocks become less important, and it may be possible to meet target concentrations without cleaning the blocks completely.

In a pneumatically fractured formation, it is probable that air flow will be proportional to fracture size, i.e., the largest flows will occur in the largest fractures. This flow channelization will not preclude at least some flow in the smaller fractures, however, as long as suitable vacuum levels are applied to the formation. Even small air flows through the smaller fracture network are capable of volatilizing and removing contaminant, thereby causing an outward diffusive gradient of the contaminant from the matrix block to the smaller fractures.

Hot Gas Injection

Hot Gas Injection technology consists of utilizing the energy generated during process operation to aid the remediation effort. Conceptually, by injecting a hot gas into the contaminated subsurface fracture network, the thermal energy of the gas would be transferred to the subsurface rock material surface and any contaminant contained thereon. The resulting rise in contaminant temperature would substantially increase its vapor pressure, which results in directly increasing the mass transport rate of the material to any gas flow through the region. Since the vapor pressure is exponentially dependent on the temperature, a modest temperature increase can achieve significant mass transport rate changes (e.g., 20°F increase will double the vapor pressure and mass transport rate of typical hydrocarbons, another 20°F will re-double, etc.).

In the application of hot gas injection technology to geologic formations, the low heat capacity of air is the major factor. This can be offset by utilizing one or both of the following approaches: 1) Injecting air at very high temperatures; or 2) Injecting very large volumes of hot air.

The first approach, maintaining very high temperatures, is cost prohibited due to the excessive energy requirements. The second approach may also be difficult, since large air volumes cannot be forced through a porous media unless the formation possesses a naturally high permeability.

As a result, utilization of conventional hot gas injection technology is impractical in the remediation of most geologic formations due to the inability of the process to develop subsurface thermal effects.

By integrating PFE with Accutech's HGI technology, the limitation of formation permeability can be overcome since the subsurface air flow in a pneumatically fractured formation will follow the "Cubic Law", substantially higher air flow rates can be developed than in a standard porous media. An additional benefit of the PFE/HGI integration can be realized in formations that contain naturally occurring fractures such as the siltstone present at the Demonstration site.

Since the natural fractures serve as the primary pathway of entry for the contamination into the formation, the largest contaminant mass will be logically in and adjacent to these natural fractures. After these fractures become dilated as a result of the PFE injection, the subsequently injected heated air will volatilize the contaminants in the vicinity of the fractures and it will not be necessary to heat the entire rock mass to access a majority of the contaminants.

The baseline subsurface temperature observed during both the pre-Demonstration and Demonstration activities ranged from 53°F to 60°F. The middle of this range is consistent with expected subsurface temperatures based upon standard geothermal gradients for these depths. The minor variations in the baseline are likely due to site activities including air extraction, which causes a slight heating effect, (extracted air ultimately comes from the atmosphere), and cooling effects induced from extraction of perched ground water.

During the Demonstration 90-hr HGI test wherein the injection temperatures ranged from 150°F to 200°F air into the formation, thermal gradients as high as 77°F were observed as much as seven and one half feet away from the injection well.

Full-scale remedial application of Hot Gas Injection technology, whether operated as a "pulsing" mode or as an active inlet well source, provides the potential to accelerate the recovery of volatile organics and to offer a method to recover semi-volatile compounds with low vapor pressures.

Applicability

Pneumatic Fracturing Extraction is applicable for removal of volatile and semi-volatile chemicals in low permeable formations. It has been demonstrated to enhance contaminant removal rates from soil formations consisting of silts and clays and moderately fractured sedimentary rock formations such as shale. Figure B-3 provides approximate guidelines for PFE application. As indicated, PFE can generally improve air flow in geologic formations whose natural air conductivity is less than 10^{-5} cm/sec through the creation of a fracture network. In formations with higher concentrations, PFE is most useful for rapid aeration and making subsurface flow paths uniform. Since no two sites exhibit the same environmental characteristics, geology, or contaminants, Accutech readily integrates the PFE process with other complementary technologies to address each site's unique remedial requirements. The following are examples of technologies that PFE has been integrated with.

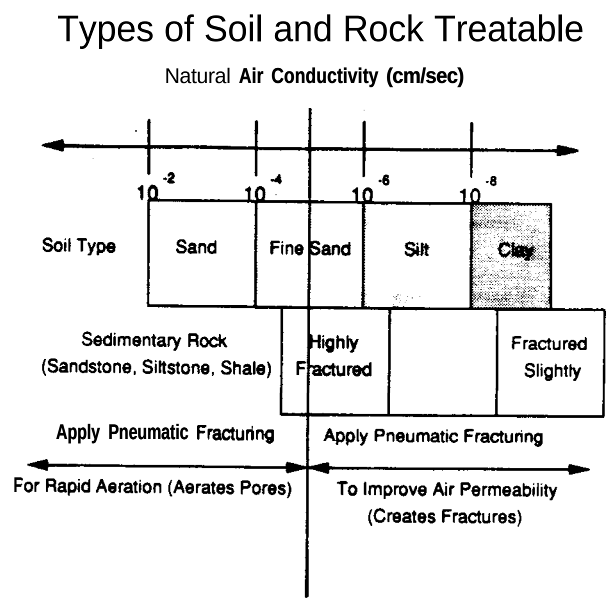


Figure B-3. Types of soil and rock treatable.

Integrated Systems

In situ Bioremediation

In situ bioremediation is a treatment technology which utilizes naturally occurring biological processes to degrade hazardous compounds. For degradation to occur, however, certain substrates such as oxygen and nutrients must be available to the soil microorganisms. Low formation permeability limits the ability for these substrates to move through the subsurface and thus can retard or prevent the desired microbial activity from occurring.

By integrating the PFE process with bioremediation techniques, the limitations of formation permeability are overcome, which allows for uniform oxygen distribution within the subsurface. Nutrients and any other necessary substrates are then injected into the formation through a process called Pneumatic Bio-injection. Thus, biological activity can be stimulated in the contaminated sections of the formation, with the hazardous compounds being degraded into harmless minerals.

PFE Saturated Zone Applications

While the EPA SITE Demonstration was focused upon vadose zone source removal, situations are encountered where the source of the contamination is located in the saturated zone. In formations where contamination is adversely affecting groundwater quality, Accutech integrates both its PFE and/or HGI processes to groundwater recovery and treatment applications.

Application of the PFE process has been demonstrated to improve recovery rates of contaminated groundwater in both soil and rock formations. In situations where free product is present in low permeability formations, PFE offers the' ability to enhance the operation of product recovery systems. Because PFE increases the formation permeability, integration of the technology with any liquid removal system will enhance the treatment effectiveness versus technologies applied in unfractured media.

PFE Sparging

Conventional air sparging combined with SVE is an emerging treatment technology for the removal of volatile organics from soil and groundwater. The air sparging technology consists of injecting air into the saturated zone at the depth of the contaminant plume. Bubbles of air then volatilize dissolved or adsorbed phase contaminants in the groundwater. Volatilized compounds are then carried to the vadose zone by the air bubbles, where they are removed through an SVE type system. As with other in situ technologies, this remedial technology can be limited by formation permeability. Even if the permeability issues can be overcome, over-pressurization can lead to uncontrolled dispersion of contamination.

Pneumatically enhanced sparging allows for the effective treatment of a larger portion of the contaminant plume more effectively. However, since radius of fracture influence is a function of PFE application parameters, the extent of higher permeability can be controlled. Therefore, the potential for over-pressurization is limited and the risk of undesirable dispersion is reduced. By substituting Hot Gas for atmospheric air for injection into the saturated zone, contaminant volatilization will be greater.

Appendix C
SITE Demonstration Results

Introduction

The objectives of this demonstration project were to: (1) study the effectiveness of the Pneumatic Fracturing Extraction (PFE) process as a means of increasing air flow rate and the. radius of influence and, consequently, increasing the removal of volatiles, specifically trichloroethene, from a low permeability bedrock formation; (2) demonstrate that fracturing had increased the permeability or the connectivity of the formation between wells; and (3) provide preliminary data on the effects of Hot Gas Injection (HGI) in terms of heat transfer and VOC removal from such formations.

The site had been used by industrial firms until a fire destroyed the building in 1985. During cleanup after the fire, the groundwater was found to be contaminated with halogenated volatile organics, primarily trichloroethene. The site was selected for evaluation of this technology on the basis of extensive soil and groundwater evaluations carried out by McLaren/Hart Environmental Engineers (and others) as part of a New Jersey Environmental Cleanup Responsibility Act (ECRA) Cleanup Plan for the site. Under New Jersey's ECRA regulations, the site may not be redeveloped until it has been decontaminated. Although this site is not a Superfund site by other definitions, it is representative of contamination and ground character encountered at Superfund sites. Figure C-l presents the general layout of the facility and the location of existing wells that were used to assess the suitability for the SITE demonstration project.

Based on analyses from these test wells (Table C-l) and others, it was concluded that the unsaturated or vadose zone was also contaminated with trichloroethene, and that the sump area near the foundation of the destroyed building was probably the source. In addition, the data suggested that the groundwater plume was moving to the northeast

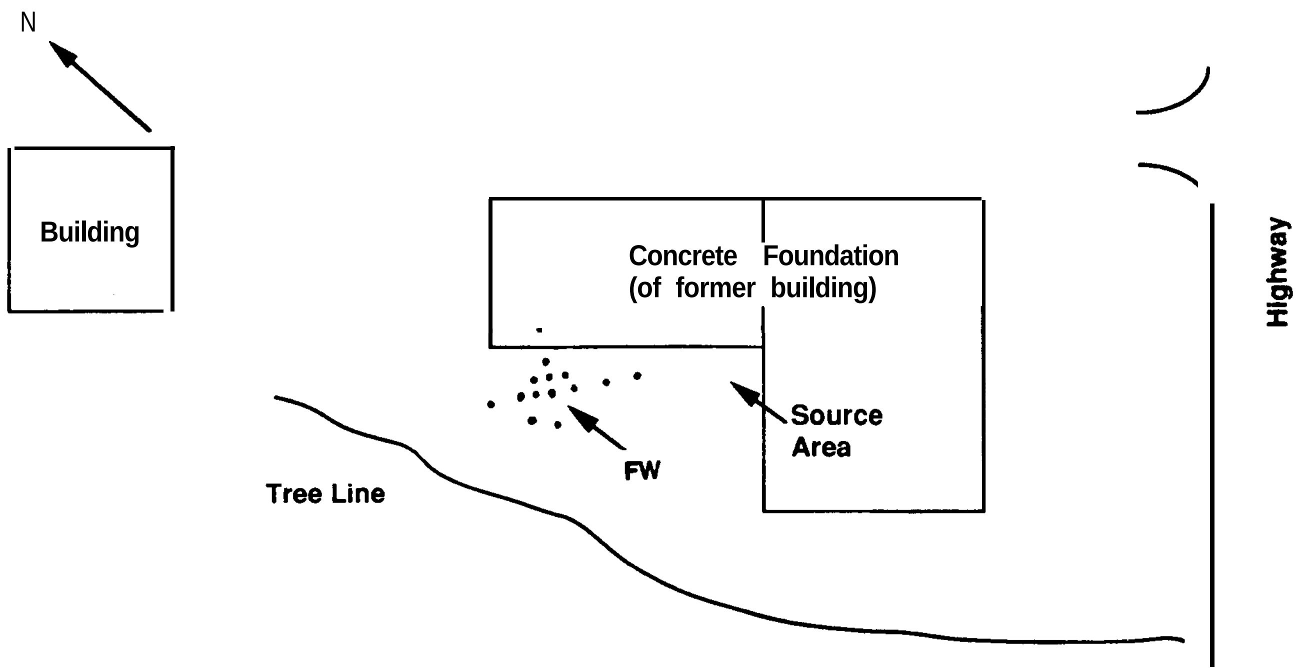


Figure C-l. Site plan.

while the vapors were moving northwest. The bedrock was characterized as part of the Brunswick formation, a highly fractured shale . From the existing studies, it was clear that TCE was present in both the groundwater and the vadose zone, with concentrations of TCE in the soil gas perhaps reaching several hundred ppmv, and concentrations in the groundwater in the <100 ppm range.

Table C-l. Analysis of Wells on Demonstration Site

Well No.	Depth, ft	TCE	DCE	PCE
Groundwater analyses, ppm (mg/L)				
MW-1S	18-50	52-70	6.9-0.2	2.5-3.0
MW-ID1	57-80	.032-045	ND-.003	ND-.003
MW-2	20-50	8.4	0.26	0.059
Soil Gas Analyses, ppmv				
VG-3	5-7	35	---	4.6J
VG-3	15-17	126	---	5.6J

J = below quantitation limit.

Considerable TCE contamination remained after the surface layer of soil (-2 to 3 ft deep) had been removed from the sump area. The fractured shale character of the exposed bedrock would make further excavation both slow and costly, even though the area is relatively small. Without removal of the source of contamination in the vadose zone, the underlying groundwater (water table at approximately 25 ft below land surface) would continue to be contaminated and would make the planned pump-and-treat remediation of the groundwater slow and inefficient. The PFE process appeared to be well suited to remediation of the vadose zone at this site, and would remove at least one significant source of groundwater contamination.

Pneumatic Fracturing Extraction

The tests were carried out in an area near but not directly in the sump area (see Figure A-5 for well placement). The primary experiment consisted of a comparison of 4-hr extraction tests before and after fracturing, in terms of both air flow rate and TCE mass removal rates. Half-hour composite samples of the extracted gas were collected at a constant rate (3 L/30 min) in Tedlar bags (EPA Method 18) and analyzed by an on-site GC within 2 hr.

A "recharge" effect often is observed when vapor extraction is stopped and then restarted, with contaminant concentrations peaking again on startup. Since a delay was necessary and planned while the central well was fractured, a second prefracture test was carried out after the system was dormant for 22 hr and the data from this test (air flow rate, TCE concentration, etc.) were used for comparison with the postfracture test.

A series of tests also were carried out before and after fracturing to evaluate the effective radius of extraction. This was done by extracting from each of the fracture monitoring wells (FMWs) while all other wells remained capped. Pressure and air flow rate were monitored for each 10-min test.

In addition, passive air inlet tests were carried out before and after fracturing by allowing air to enter one or more monitoring wells while air was extracted from the fracture well. Pressure, air flow rate, and TCE concentration were monitored at the extraction well.

Brief tests also were carried out before and after fracturing of each interval to learn whether significant vertical connections were initially present or were created by fracturing . This was accomplished by extracting from each fracture interval while the packer assembly was still in place and monitoring pressure, air flow rate, and TCE concentration.

Hot Gas Injection

In anticipation of future investigation of catalytic oxidation of TCE in the extracted air stream and injection of the hot exhaust gas into the formation (Possible Phase II study), two experiments were carried out to evaluate the effects of HGI. These tests provided data for HSMRC to use in their development of a model for transient heat transfer in a fractured formation, and also provided data on TCE removal.

In the first HGI experiment, the existing field of wells was expanded by installing four thermal monitoring wells at about 5 and 7 ft distances from the fracture/injection well, as shown in Figure A-5. Pressures, temperatures at varying depths in each monitoring well, and TCE removal rates from the extraction well were measured over the course of a 90-hr test while hot air (-200°F to **250°F,** 15 to 24 psia, and 65 to 75 scfm) produced by compression heating was injected into the fracture well.

In the second test, two additional 4-in. wells (IW2 and FMW8 in Figure A-5) which intersected a more contaminated zone were installed. Wells number FMW6 and FMW8 (new) were manifolded together and used as extraction wells while hot air was injected into well IW2. This experiment was carried out for 24 hr while temperature, air flow rate, and pressure were monitored and I-hr composite samples were collected in Tedlar bags for immediate analysis by GC. No additional fracturing was carried out.

Field Activities

Accutech and HSMRC were responsible for the specifications and locations for the wells, which were drilled under the direction of SAIC's Field Manager/Geologist. Accutech and HSMRC were responsible for fracturing the central well and for operating the extraction system. SAIC obtained and recorded the bulk of the pressure, flow, and temperature data, but HSMRC also recorded comparable data in most instances using other equipment. Tedlar bag samples were collected by SAIC's subcontractor, IEA Laboratories, and analyzed on-site by gas chromatography. A limited number of Tedlar bag samples also were collected during the course of the project for more complete analysis by GC/MS using CLP Methods at IEA's Connecticut laboratory.

Although it had been anticipated that the vadose zone would be relatively free of water, considerable water was present and gradually filled all the wells. All parties collaborated on daily pumping of the wells before each experiment in an attempt to maintain the most constant depth of open hole in all wells. Over the course of the 4-wk investigation, there were indications that the water recharge rate was decreasing, but the water problem persisted throughout the study. Presumably, some TCE was being removed in this water, but the volume of water and the TCE concentration were not measured during the study. Even if such data were obtained, it would not have been possible to attribute the values to any particular experiment. (A single analysis of the water by EPA Method 8010 indicated 0.130 ppm of TCE; a sample taken later in preparation for disposal indicated a very low concentration, 0.044 ppm, of TCE, and no other contaminants.)

Test Procedures

After considering several alternatives, a modified EPA Method 18 sampling procedure was chosen to collect samples of the extracted air. Duplicate samples of the extracted air were collected in evacuated 3-L Tedlar bags at uniform rates over 0.5 hr intervals during most of the study. For certain experiments, the sampling time was increased to 1 hr and for others it was only 10 min. A small impinger was included in the Method 18 sampling train to collect any entrained water for TCE determination by Method 8010 so that its mass could be added to the amount measured in the gas. Surprisingly, although considerable water accumulated upstream in the knockout trap on the extraction trailer and water certainly was present in the vadose zone, no water was found in the impinger during any experiment.

An in-line Organic Vapor Monitor (OVM, Foxboro Model 580B) was also installed in a "T" off the manifold so that total volatile hydrocarbons could be correlated with the TCE measured by GC. Unfortunately, the OVM and substitute HNu instruments repeatedly failed, making this data collection effort incomplete.

Air in the exhaust stack after the carbon adsorber was monitored daily using an OVA or HNu calibrated against isobutylene and occasionally cross-checking these results with GC analysis of Tedlar bag samples. This assured that the final exhaust from the system met the air monitoring requirements imposed by the New Jersey DEPE. Ambient air quality was also monitored for VOCs by OVA (or HNu) during all test activities, particularly the beginning of the HGI test when odors detected along the perimeter of the foundation raised concern about worker safety.

Results

Air Flow Impact of Fracturing - Monitoring Wells Capped

Based on a comparison of the air flow extracted from the fracture/extraction well during the 4-hr prefracture (restart) test with that after fracturing, the air flow rate (corrected to standard conditions of 1 atmosphere and 60°F) increased about 600% (Table C-2). Figure C-2 graphically presents the air flow data before and after fracturing.

Table C-2. Effects of Fracturing, 4-hr Tests

Parameter	Pre-fracture	Prefracture Restart	Post-fracture	Increase *, %
Pressure, psia	11.1	11.1	11.4	---
Air flow, scfm	<0.6#	<0.6#	4.2±0.6	600
TCE mass removal, 10^{-6}lb/min	<10.9	<11.0	83.9±31	675

* increase = 100 x (postfracture-restart)/restart.
# HSMRC data indicate air flow **<0.6 scfm.**

Trichloroethene Removal Before and After Fracturing

Although the concentrations of TCE in the extracted air did not increase much as a result of fracturing (prefracture average: 50 ppmv; postfracture average: 58 ppmv), the TCE mass removal rate during the 4 hr increased about 675%, largely as a result of the large increase (600%) in air flow rate. These results are also summarized in Table C-2 and in Figure C-3. A significant change in TCE mass removal rate was not observed when extraction was restarted after the 22-hr dormant period, suggesting that recharging while fracturing was carried out was not a significant contributor to the increased TCE mass removal rate observed in the postfracture test.

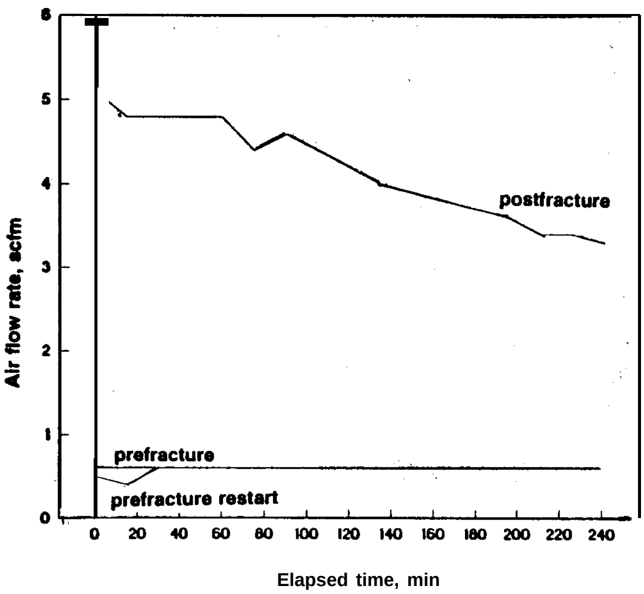


Figure C-2. Comparison of 4-hr air flow rates.

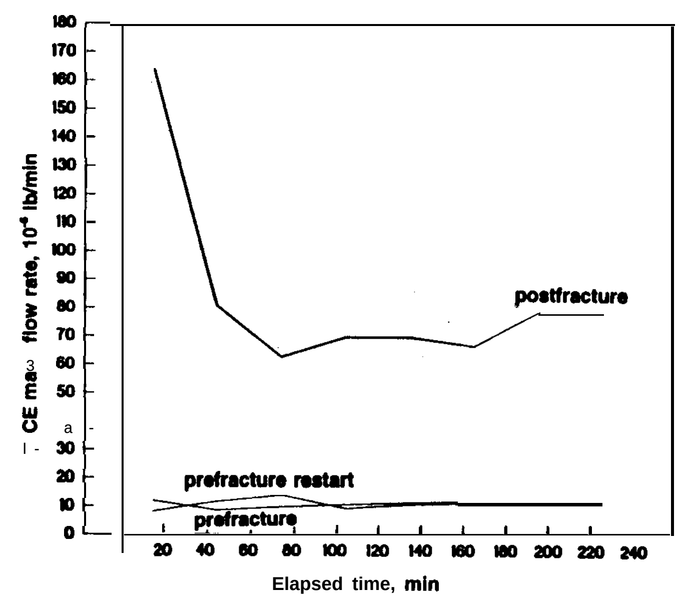


Figure C-3. Comparison of 4-hr TCE mass removal rates.

The postfracture test was also extended 2 hr so that additional data could be accumulated. During the added 2 hr, after again dewatering the wells, both air flow and TCE concentration increased further (5.0 scfm and 70 ppmv, respectively). The calculated increase in TCE mass removal rate after fracturing, based on the 6 hr of operation, was 800%. Removal of perched water from the well bores between the two segments of the postfracture test also may have contributed to increased air flow rate and/or exposure of new pockets of contamination and, consequently, to increased TCE removal.

Physical Impact of Fracturing on the Formation

Analysis of tiltmeter data collected by HSMRC personnel during the fracturing events indicated that measurable surface heave was detected as much as 20 ft away from the fracturing well and appeared to favor the strike direction to a small extent. Computer-derived contour maps of the fracturing events were developed by HSMRC; the series of these maps for one fracturing interval showing the change with time are presented in Figure C-4.

A profile of maximum pressures in all the monitoring wells during the actual fracturing events (Table C-3) also suggests that fracturing direction is relatively uniform, and that more distant wells are less affected. Although considerable pressure is transmitted to monitoring wells even 20 ft from the fracturing well, uncertainty about water levels in one or more wells makes more detailed use of these results questionable.

Table C-3. Maximum Pressure During Fracture Events

Monitor Well No.	Distance to FW, ft	Maximum Pressure, psig in Interval, ft bls 9-11.1	11.1-13.3	13.1-15.3	14.5-16.4
FMW1	10	16	18	23	23
FMW2	10	14	18	23	21
FMW3	10	15	17	22	19
FMW4	10	18	18	23	22
FMW5	20	14	14	15	11
FMW6	7.5	19	20	22	25
FMW7	20	12	15	15	11

Direct examination of the effects of pneumatic fracturing on the formation was made with a borehole camera. Comparison of prefracture and postfracture videos revealed a widening of existing discontinuities and the appearance of some new fractures. When the camera was operated during vacuum extraction, the pulsing of water into the borehole from certain fractures was very evident.

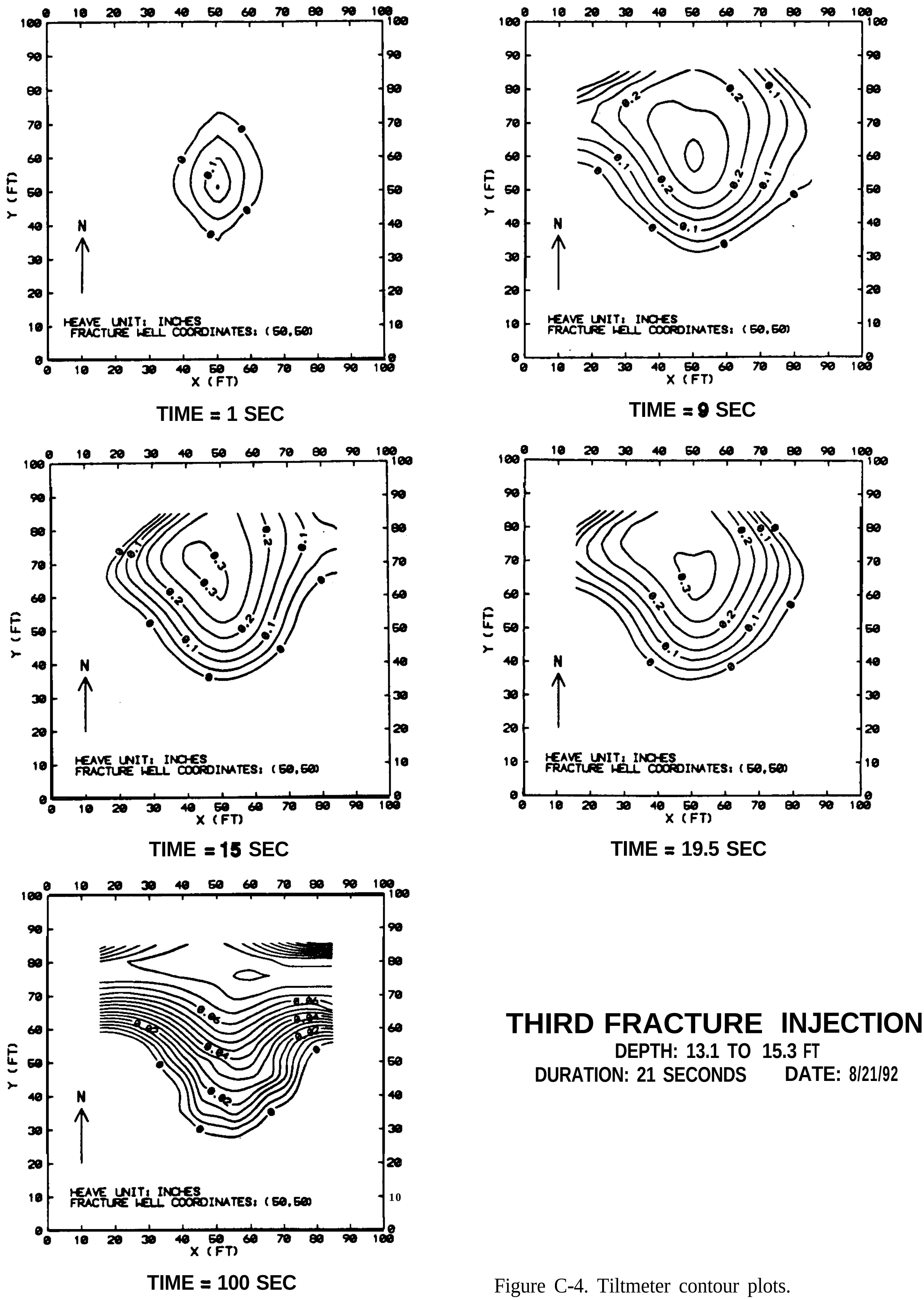


Figure C-4. Tiltmeter contour plots.

Similarly, measurements of pressure and air flow rates during short term (10 to 15 min) extraction tests at individual monitoring wells before and after fracturing suggest (a) that a connection probably existed between the fracture well and monitoring well FMW6 before fracturing and (b) that there was a considerable increase in permeability or connection in all directions after fracturing (Table C-4). These observations must be considered cautiously since perched water may have interfered with valid data from one or more wells.

Table C-4. Monitoring Well Extraction Tests

Distance from FW, ft	Well No.	Air flow rate, scfm avg pre-fracture	Air flow rate, scfm avg post-fracture	Increase, % avg
7.5d*	FMW 6	<.89^	6.1	>580
10 s	FMW 1	<.63	5.6	>790
10 o/s	FMW 2	<.72	6.1	>720
10 d	FMW 3	<.63	7.2	>1040
10 s	FMW 4	<.63	6.9	>1000
20 s	FMW 5	<.63	6.5	>930
20 d	FMW 7	<.63	2.0	>220

^ these results are based partially on HSMRC data.
* s = strike; d = dip; o/s = off strike and dip.

Passive Air Inlet Tests

Extraction tests before and after fracturing with one or more wells open to the air (passive inlet mode) indicated a very large increase in air flow rate and consequently, in TCE mass removal rate (Table C-5). Using this mode, the TCE mass removal rate after fracturing was about 40% greater than that observed during extraction with all the monitoring wells capped. Although the SAIC pressure gauges used to calculate air flow rates remained essentially at "0") rotameters used by HSMRC indicated values ranging from 0.3 to 0.6 scfm in the prefracture test.

Table C-5. Passive Air Inlet Tests

Parameter	Prefracture	Postfracture	Increase, %
Pressure, psia avg	10.8	**14.6**	---
Air flow, scfm avg	0.39±.04	76.4±4.8	19,500
TCE mass removal rate, 10^{-6}lb/min	4.8±1.4	116.0±91	2,300

Effect of Hot Gas Injection

In the first HGI experiment, lasting 90-hr, temperature increases were observed in wells at different distances and different depths, usually at an 8 ft depth. These increases were greater at the monitoring wells closer to the hot air injection well, and may have reached a maximum before the first readings were taken at the 8 ft depth, after 20 hr. Unfortunately, the thermocouples were at the 14 ft bls depth during the first 20 hr and may have been submerged in water at that depth. In addition, extraction was taking place only from FMW5 during the initial 20 hr. Because very low TCE concentrations were observed, Accutech manifolded three other wells (FMWl, 3, and 6) together with FMW5 at that time, resulting in increased extracted air flow rates subsequently. When compared with a 4-hr baseline test during which air was extracted from the same FMW5 well, but no air was injected into the central fracture/injection well, it was apparent that HGI did not substantially increase the TCE mass removal rate in the extracted air, even when multiple wells were manifolded to the extraction system. Table C-6 and Figure C-5 summarize the air flow and TCE mass removal results, and Figure C-6 graphically describes the temperatures observed in the different capped wells.

Table C-6. Hot Gas Injection Test, 90 hr

Parameter	Pre-HGI-1	HGI-1*	Increase, %
Extraction pressure, psia avg	10.9	13.4	---
Air flow rate, scfm avg	11.6±1.5	82.6±7.1	612
TCE mass removal rate, 10^{-6}lb/min	172±18	31.2±10.3	-82

* Results shown are for 22-90 hr period; 4 extraction wells on manifold.

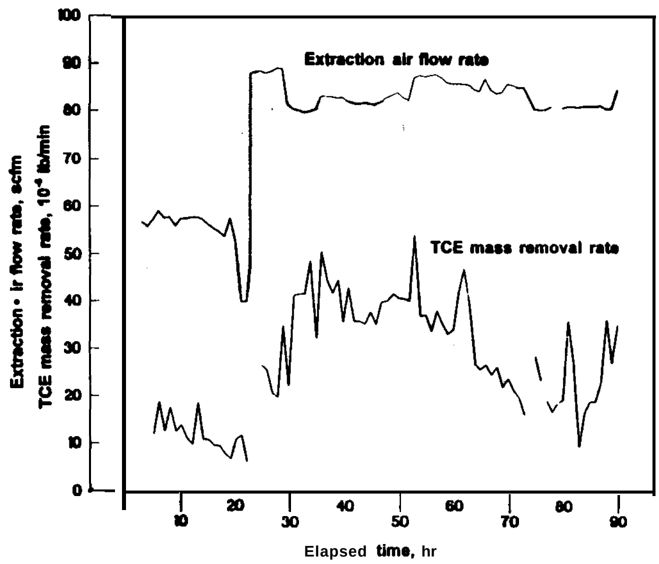


Figure C-5. Air flow and TCE mass removal rates.

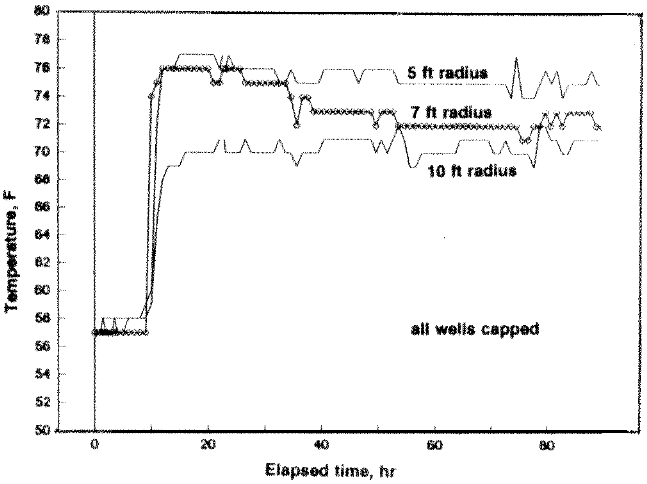


Figure C-6. Temperature in wells, 90-hr HGI test,

Interestingly, when HGI was discontinued, the temperature in some of the wells continued to increase for some time. This may be due to the air flow convectively cooling the thermocouples during hot gas injection and extraction but not during the post test when the. air was shut off.

Because one explanation considered for the low TCE removal was that the TCE in this area had been exhausted, a brief (3-hr) follow-up extraction test was carried out as a comparison with the original postfracture extraction test. The results of this test, with extraction from the same FMW5 with all other wells capped, indicated that TCE still could be removed by vapor extraction at a TCE mass removal rate of 82 x 10^{-6} lb/min. Similarly, when a 1-hr post-HGI extraction test was carried out from the fracture well (FW), as in the original PFE tests, the formation again yielded a TCE mass removal rate of 95.1 x 10^{-6} lb/min. It could, however, be argued that during HGI different pockets of the bedrock were being accessed.

A second HGI experiment was carried out in an area believed to be more heavily contaminated and where connection between wells had been observed during the original fracturing event. NO ADDITIONAL FRACTURING WAS CARRIED OUT. Hot air was injected into a central well (IW2) and extracted from two outer wells (FMW6 and FMW8), each -10 ft distant. When these results were compared to a baseline in which no hot air was injected, the TCE mass removal rate extracted increased about 53%, significantly less than the 150% increase observed in the air flow rate. In this case, however, no increase in temperature was observed in the extraction wells, which may be due to the short duration of the test. These results are summarized in Table C-7 and presented graphically in Figure C-7.

Table C-7. Hot Gas Injection Test, 24-hr

Parameter	Pre-HGI-2	HGI-2	Increase, %
Extraction pressure, psia avg	11.0	11.8	---
Air flow rate, scfm avg	3.7±1.8	9.2±4.7	150
TCE mass removal rate, 10^{-6}lb/min	63±27	97±33	54

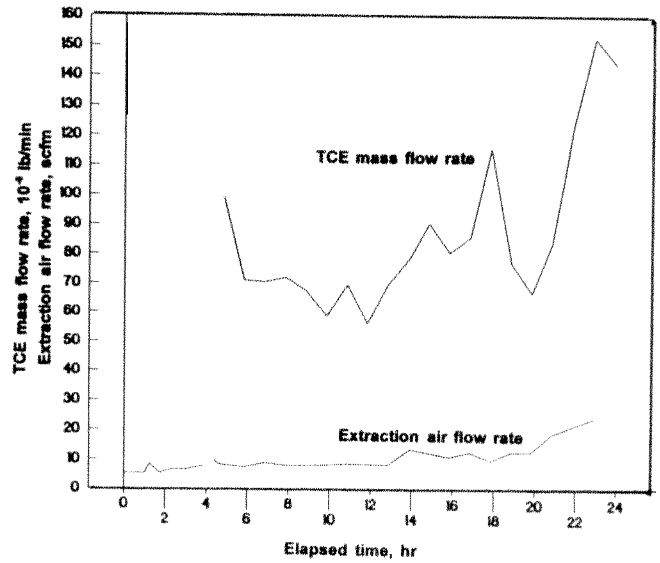


Figure C-7. TCE mass removal rates, 24-hr HGI test.

Several explanations have been considered for the anomalous results from the two experiments, including: no available TCE in the formation or short-circuiting, water at higher and variable depths in some wells, unsuitable control experiment, solar heating of the air in the extraction wells, cooling effect of moving air, etc.

GC/MS Analysis of Gas Samples

Concentrations of the various volatiles in the extracted air samples were somewhat surprising. Although TCE was a prominent contaminant, it was not always the predominant one. Particularly in the postfracture extraction, it was clear from the complexity of the VOC scan in the field-GC analyses that many other constituents were now being extracted. This was confirmed by GC/MS analyses (Table C-8). Similar constituents, but at lower concentrations, were also found in the air samples examined during HGI. It is unclear what caused the increase of other classes of compounds in the postfracture sample, but it may be speculated that pockets of absorbed or NAPL organics were accessed.

Table C-8. GC/MS Analysis of VOCs in Extracted Air

Contaminant	PFE Tests		HGI Tests		
	Prefracture	Postfracture	PreHGI-1	HGI-1	HGI-2
	Concentration, ppmv				
methylene chloride	1.4	26.0	11.9	0.93	3.6
chloroform	3.5	108.5	40.2	3.2	1.5
c-1,2-dichloroethene	U(<3.)	U(<12.5)	21.8	1.2	2.2
trichloroethene	59.4	113.4	49.4	10.2	18.6
benzene	5.4	412.7	107.8	7.1	3.4
tetrachloroethene	3.3	220.4	92.8	4.3	7.5
toluene	U(<3.3)	5.2J	1.8J	U(<.6)	U(<.5)
xylene, m/p-	U(<2.8)	U(<11.4)	5.0	0.25	U(<.5)
xylene, o-	U(<2.8)	U(<11.4)	3.2	0.2J	U(<.5)

U = below detection limit
J = no definition available, probably below quantitation limit

Although these VOCs were measured in an essentially closed system, the presence of elevated concentrations of benzene must serve as a warning that careful monitoring and personal protection must be employed during well installation, during fracturing, and at any other times when unexpected exposure could occur.

Quality Assurance

The critical analysis of trichloroethene (TCE) was performed on-site using capillary column gas chromatography and a flame ionization detector. Samples were collected in Tedlar bags and analyzed in accordance with EPA Method 18. Extensive QA/QC procedures were specified and followed, including initial and continuing calibration protocols, blank analyses, second-source standards, audit gas analyses, replicate. injections, and duplicate sample analyses. Accuracy was evaluated through the analysis of second-source standards and audit gases; these analyses generally met specified criteria **(±10%),** although some low concentration standards were outside the limits. The potential bias in TCE concentrations reported at values near the detection limit of 1.0 ppmv has limited impact on project objectives since these results were not from critical tests. Precision, as assessed by duplicate sample analyses, was generally excellent with most RPD values less than 10% for sample pairs with TCE concentrations above the detection limit.

Critical process determinations included flow rate, temperature, and pressure. There exists a slight potential for a maximum 20% error in some reported pressure values; some pressure measurements may not have been corrected as required, based on parity plots of the calibrated gauge, when the specific gauge used was not documented.

In general, data generated for this project were determined to be of sufficient quality to provide for the proper evaluation of test objectives.

Appendix D-l
Soil Vat Tests

Basic evidence for the benefits of pneumatic fracturing were first obtained by laboratory tests carried out at HSMRC.

A series of plexiglass vats were filled with soils containing a surrogate contaminant. The vats were equipped with a central nozzle connected to laboratory compressed air (60 psig) for fracturing. Extraction tubes were located in the four comers of the vats. Vacuum extraction tests could be carried out using vacuum, positive pressure, or a combination of both.

Two different soil types were tested, a silty sand (United Classification "SM") and a silty clay (United Classification "CL"). The surrogate contaminant was alcohol in water, which avoided any problems with disposal.

Test results with these systems and soils indicated increases in contaminant removal by 100% to 360% after fracturing, compared to vacuum extraction or air injection of unfractured soil, respectively.

Table D-1. Vat tests of Pneumatic Fracturing

Test no.	Soil type	Extract mode	Surrogate conc, %	Soil density before lb/cf	Soil density after lb/cf	Increase in removal, %
PF-3	SM	AI*	14.7	101.1	88.6	320
PF-4	SM	AI	13.8	102.1	91.8	170
PF-5	SM	VE/AI	15.8	100.2	92.3	100
PF-6	CL	AI	10.6	100.2	84.7	230
PF-7	CL	AI	14.8	112.0	98.5	185
PF-8	CL	VE	14.0	111.4	103.5	145
PF-9	CL	VE	14.0	121.5	108.5	140
PF-10	CL	VE	15.9	99.3	93.5	180
PF-11	CL	AI	15.7	100.7	92.1	360

* AI = air inject, VE = vacuum extraction

Conclusions

1. Pneumatic fracturing consistently increased contaminant removal, by rates ranging from 100% to 360% greater than in unfractured extraction.

2. The increases in contaminant removal are primarily attributable to increases in air flow in the fractured soil.

3. Soil type affects the benefits of fracturing. Finer grained soils exhibit more gradual contaminant loss, which is consistent with their lower permeability.

Appendix D-2
Test Site - Newark, NJ

Background

A series of pneumatic fracturing tests were performed at a clean site located on the NJIT campus in Newark, NJ. The purpose was to evaluate the effects of fracturing on sedimentary bedrock using ground surface heave and formation permeability. All tests were conducted in the vadose zone, and were continued over a period of 8 mo to examine the effects of fracture longevity in rock. The site was located in an active parking lot which was subjected to car and truck traffic throughout the study period.

The site is underlain by the Brunswick Formation which consists of fractured siltstones and sandstones. A single 28 ft deep well was drilled to serve both as a fracture well and an extraction well. It was cased to a depth of 4 ft, below which the well remained uncased with a 3-in. bore. The water table fluctuated between 21 and 25 ft deep throughout the study period.

Test Procedure and Results

Baseline air permeability was measured by extracting through a double packer system in 2-ft intervals over the depth range of 7 to 19 ft. Total well behavior was also measured by extracting from the entire well. All air flows were measured at a standard vacuum of 20 in. H_2O. Fracture injections were then made at two discrete depth intervals: 9 to 11 ft and 15 to 17 ft. The profile of air permeability was measured again to evaluate the changes in air flow caused by the fracturing. Ground surface heave was monitored during fracturing with a reference beam system.

The permeability tests showed that the air flows in the fracture zones increased 9 to 14 times as result of fracturing. The air flow in the 9 to 11 ft zone increased from 2.1 scfm to >10.5 scfm, and the air flow in the 15 to 17 ft zone increased from 0.5 scfm to 7.2 scfm. The effects of the fracture injection on the 9 to 11 ft zone is summarized in Figure D-l, which also depicts the visual log for the rock core.

Air flow measurements were repeated over a period of 8 mo during which the area was subjected to car and truck trafftc. The fractures remained viable throughout the study period and no significant fluctuations in air flow were observed. The long term flow behavior of the 15 to 17 ft fracture zone is shown in Figure D-2.

Ground surface heave measurements made during injection indicated that the fractures propagated at least 10 ft in all directions. Maximum ground surface heave for the 9 to 11 ft zone was 0.16 in., and 0.13 in. at the 15 to 17 ft zone. No discernible effects were observed on the asphalt pavement which covered the test site.

Conclusions

Pneumatic fracturing successfully enhanced the permeability of sedimentary rock from 5 to 14 times. Long term studies showed that fractures remained viable in rock for at least 8 months. Measurement of downhole fracture injection pressures suggested that the principal mechanism of permeability enhancement is dilation of existing rock discontinuities. Ground surface heave measurements showed that fracture radii exceeded 10 ft.

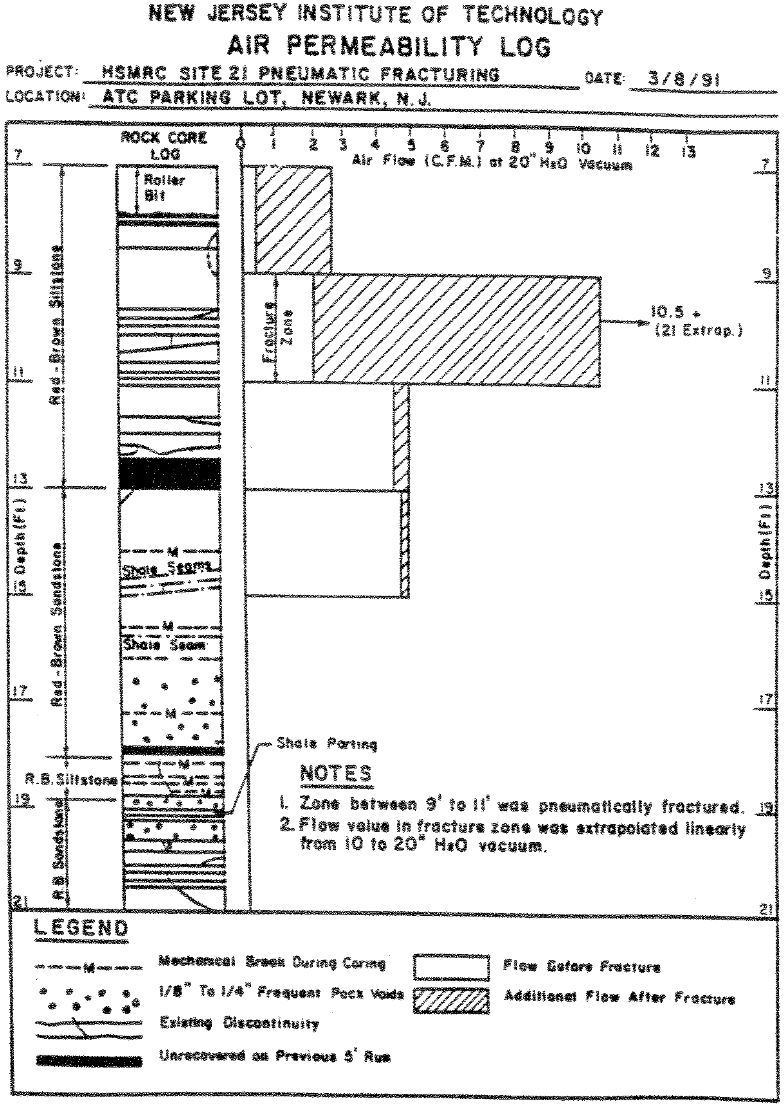


Figure D-1. Air permeability log, 9-11 ft fracture zone.

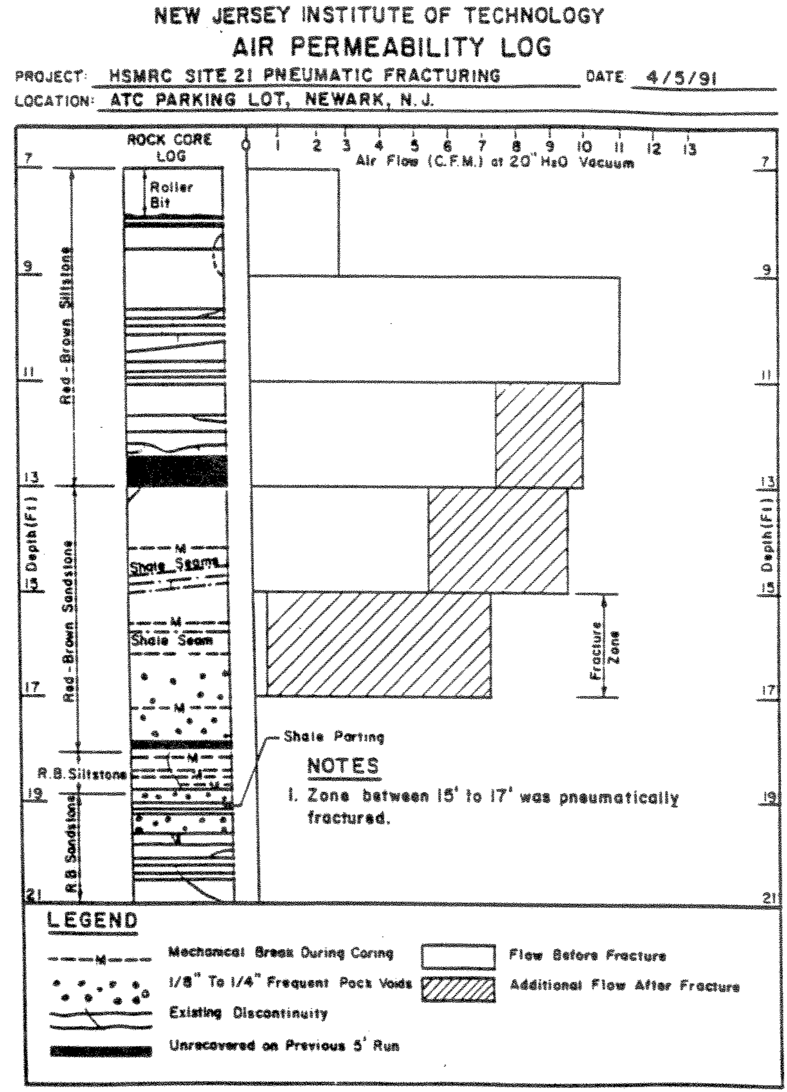


Figure D-2. Air permeability log, 15-17 ft fracture zone.

Appendix D-3
Former Tank Farm - Richmond VA

Background

An abandoned section of a tank farm in Richmond, Virginia was the location of this demonstration of Pneumatic Fracturing Extraction. The formation at this site consisted of highly overconsolidated stiff clay, (United Classification CH-MI-I) which was overlain by a clayey silt and in some sections by a concrete slab. All fracture injections were made between 5 to 10 ft below grade in the stiff clay layer.

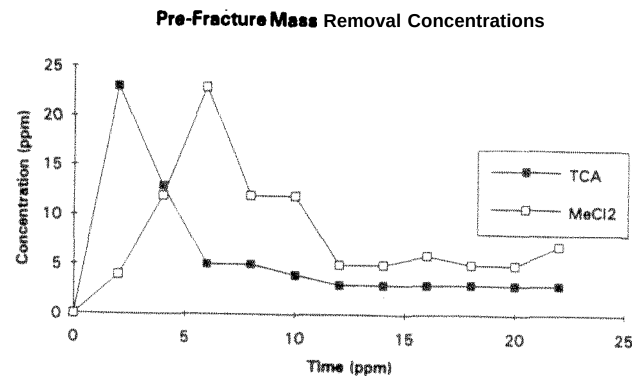
The aboveground tank at this site had been removed with only the concrete slab remaining. Soil samples taken from the vadose zone indicated that methylene chloride (CH_2Cl_2) and trichloroethane (TCA) were the principal contaminants of concern. An adjacent sump seemed to be the source of contamination.

Results

Baseline conditions were established for both air extraction flow rate and contaminant mass removal. These tests confirmed the extremely low formation permeability, as the flow rates were less than 0.00071 scfm, which was the lower limit of the flow measurement system. The removal rate for both contaminants peaked at about 23 ppm, and neared a non-detect level after 35 minutes. Contaminant concentrations were measured using a gas chromatograph.

During pneumatic injection events, surface heave was measured to be over 1 in. in some spots. Although the concrete pad did deflect some of the injection influence, fractures were detected below the concrete pad.

Following pneumatic injections, the formation permeability greatly improved as indicated by the 4,900% increase in air extraction flow rates. Contaminant extraction concentrations peaked at 8,677 ppm for CH_2Cl_2 and 4,050 ppm for TCA as shown in Figure D-3. The concentration of CH_2Cl_2 leveled off to about 200 ppm, which was still far above the concentrations that were detected before application of the PFE process.



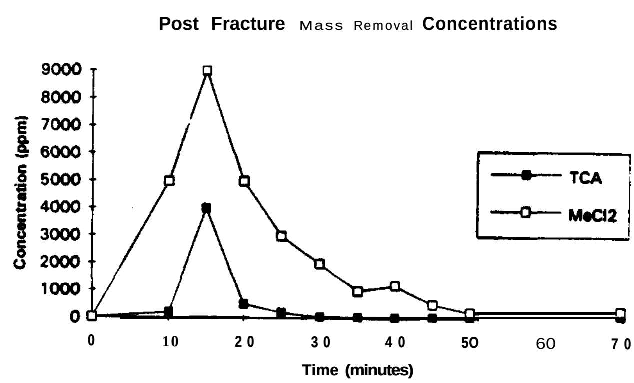


Figure D-3. Effect of fracturing, Richmond, VA site.

Conclusions

PFE increased both the extraction air flow rate and the concentration of contaminants in the extraction stream. It was also demonstrated that the injections from this process created fractures below the existing concrete slab.

Appendix D-4
Industrial Site - Newark, NJ

Background

A pilot test of Pneumatic Fracturing Extraction (PFE) was performed at an industrial site in Newark, NJ. The test was conducted in a clean portion of the site in order to demonstrate an increase in formation permeability. Fracturing on this site occurred both in the vadose zone and in the saturated zone.

The geology of the site consisted of an approximately 6-in. to 12-m concrete cap over 18 in. of gravel. This was followed by an unconsolidated zone consisting of urban fill overlying natural sediments of silts, clays, and sands. At the outset of the test, the depth to groundwater was measured at 5.1 ft below grade. A single 4-in. fracture well (3-in. open-bore) was installed in the selected clean section of the site. This well was surrounded by four monitoring wells at distances ranging from 7.5 to 18 ft from the fracture point.

Results

Baseline conditions were established for both extraction flow rate and vacuum radius of influence. Total well extraction with monitoring wells sealed yielded an effluent flow rate of 4.7 scfm. Vacuum influence measurements taken during this test ranged from 2 to 12.5 in. (of water) at the monitoring wells. Operating the extraction system utilizing the monitoring wells as passive inlet wells increased the extraction flow rate to 6 scfm.

The PFE technology was applied to two intervals. The first fracture interval (4.0 to 6.2 ft below grade), intersected the water table, which was at 5.1 ft. A second fracture interval (5.0 to 7.2 ft), was located completely in the saturated zone.

The surface heave observed during the pneumatic injections ranged from 0.16 to 0.19 in. After all PFE injections had been completed, the air extraction flow rates increased to 15.26 scfm. All monitoring wells measured an increase in vacuum pressure, which ranged from 8 to 30 in. of water. Operating with passive inlet wells, extraction flow rate increased to 17.5 scfm.

Conclusions

PFE was effective in increasing the extraction air flow rate at this site almost 400%. The process was also effective in increasing the effective vacuum radius of influence. Calculations showed that the area under remedial influence increased from 143 sq ft to 380 sq ft due to the PFE process.